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RELATING LAND COVER AND CHANNEL MORPHOLOGY TO STREAM FLOW FUNCTION IN THE LOWER PEE DEE WATERSHED, SOUTH CAROLINA

Zachary Smoot

Clemson University, ZSmoot@gmail.com

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**RELATING LAND COVER AND CHANNEL MORPHOLOGY TO STREAM
FLOW FUNCTION IN THE LOWER PEE DEE WATERSHED, SOUTH
CAROLINA**

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Biosystems Engineering

by
Zachary Thomas Smoot
November 2011

Accepted by:
Anand D. Jayakaran, Committee Chair
Dara M. Park
Daniel R. Hitchcock

ABSTRACT

The South Carolina Pee Dee Project (SCPDP) aims to develop a method for the determination of Minimum Allowable Flows (MAFs) in streams in the Pee Dee region. This study is a portion of the larger SCPDP, focusing primarily upon analyses of geomorphic and hydrologic processes, as well as landscape and habitat analyses. Specific objectives include: 1) To distinguish the effect of various land cover classes and scales of analyses on components of stream flow function; 2) To determine trends in hydraulic geometry (regional curves) for the SCPDP region; and 3) To determine what measures of stream flow function, stream geomorphology, and land cover most influence characteristic bed material. Results show that measures of land cover were found to influence components of stream function. Influential land cover classes included wetland and forest, as well those with higher curve numbers, especially those linked to agricultural and developed land cover classes. Influences of land cover on components of stream flow function were found to be spatially limited. While stream flow behavior (Richards-Baker Flashiness and Hammer Number) tended to be most influenced by larger scales, physical components of the stream (bed material and temperature variation) tended to be most influenced by smaller reach scales. Hydraulic geometry was highly influenced by catchment area. Regional curves were derived in a form similar to those found in literature. However, these curves were found to differ considerably between study regions. Characteristic bed material appears to be influenced by Richards-Baker Flashiness (RBI) and Hammer Number (H), but also seemed to be affected by impoundments and downstream fining, although this was not statistically confirmed. Measures of stream flow function were also found to be correlated to each other. These correlations were between RBI and H, the Qualitative Habitat Evaluation Index (QHEI) and bed load flux, and RBI and temperature variation. Such findings will be useful in identifying a method to determine of a Minimum Allowable Flow (MAF) for the Pee Dee region, as well the determination of physical stream state.

Key words:

Minimum Instream Flows, Minimum Allowable Flows, Coastal Plain Streams, Sediment transport, Channel morphology, Flashiness, Hammer Number, Regional Curves, Hydraulic Geometry, QHEI, Land Use, Curve Number, Land Disturbance Index, Total Impervious Area, Stream Temperature Variation

DEDICATION

I dedicate this to Emily and my Family. Without their love, prayers, and guidance, I would not be who and where I am today.

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1 INTRODUCTION

The World Meteorological Organization defines low flows as “the flow of water in a stream during prolonged dry weather.” In 1980, flows in many of California’s streams and rivers became so low, that it resulted in the absence of migration routes for steelhead trout and Chinook salmon, and a stark decline in these species populations lead to the recognition of need for legal regulation in California (Williams and McHugh, 1990). In 1992, the Earth Summit (in Rio de Janeiro) identified conservation of all ecosystems as beneficial to the public (Acreman and Dunbar, 2004). Water scarcity is not limited to a particular region, and as water resources become increasingly scarce, the conservation of the integrity and viability of all water sources will continue to become more of a necessity. Looking towards the future, we must find ways to properly manage modified ecosystems in a way that meets public needs while maintaining ecological stability, and therefore ecosystem services.

Environmental flows, also known as instream flows, environmental allocation, or minimum allowable flows (MAFs) are the attempt to maintain the ecological viability of a riverine system, or to protect river health (Acreman and Dunbar, 2004). Stream flow function, or river health, is a measure of the stability of a riverine ecosystem and its components. These components include flow discharge, riparian and riverine geomorphology, water quality, natural channel management (cutting of riparian vegetation, dredging, etc.), level of exploitation (i.e. fishing, boating, etc.) and the existence of physical barriers that affect the natural stream connectivity (Acreman and Dunbar, 2004).

The goal of all environmental flows is to design a flow plan that will effectively balance public water usage and necessary flows to maintain river health, an intention that has existed since the Clean

Water Act¹ (United States Environmental Protection Agency, 1972). As a result, some 203 different methodologies had evolved by 2003 (Tharme, 2003). While the first methods involve the determination of minimum allowable flows (MAFs), they have since evolved into what can be categorized to include look-up tables, desk-top analysis, functional analysis, and hydraulic habitat modeling (Acreman and Dunbar, 2004)², with each method having its own merit.

The South Carolina Pee Dee Project (SCPDP)

The concern for South Carolina's water resources is not a new issue. However, the government allocation of these resources is. In 2009, a bill was introduced to the South Carolina State Legislation that would regulate instream flows throughout the state. This bill passed in 2010 (A247 – South Carolina Surface Water Withdrawal, Permitting, Use, and Reporting Act, 2010³). The purpose of the SCPDP is to take a proactive approach that will help establish a baseline for waters in the Pee Dee region. As part of this study, the SCPDP is committed to the development a method for establishing MAFs across the state, starting with the Pee Dee region. The SCPDP will combine the analysis of multiple components of the riverine system, including, but not limited to, geomorphic components, landscape analyses, hydraulic monitoring, water quality observations, and the sampling of fish⁴ and macroinvertebrate assemblages.

This study is only a portion of the much larger SCPDP, focusing primarily upon analyses of geomorphic and hydrologic processes, as well as landscape and habitat analyses. Such physical

¹ Also: Federal Water Pollution Control Act (33 U. S. C. 1251 et seq.)

² As an additional resource, many of these methods have been compiled and summarized in Appendix A1.

³ Introduced in February of 2009, and sponsored by Senators Campbell, Leatherman, Reese, Shoopman, Williams, Mulvaney, Pinckney, O'Dell, Ford, Knotts, Bryant, Land, Grooms, Hutto, Fair, Peeler, Sheheen, Ryberg, Massey, Elliott, Alexander, McGill, Bright, L. Martin, Matthews, Setzler, Rose, Hayes and Campsen, Bill A247 aimed to maintain minimum flows in streams labeled for various uses. Such uses include, but are not limited to, boating and migration.

⁴ Although not included in this document, a brief literary review and preliminary data can be found in Appendix A2.

features of the riparian system are intimately intertwined with the biology/ecology of the system (Bedoya et al., 2009). Adapted from the original SCPDP hypothesis, the hypothesis outlined for this study fall in line with the SCPDP's goals for the development of MAFs for the Pee Dee region by investigating the causes of variation in the region while determining references of natural stream function, flow rates, and hydraulic geometries. These natural reference points of components of stream flow function⁵, which are measures of stream system health, help to determine stream condition. The null hypotheses investigated were:

H_{0a}: Measures of land cover do not influence components of stream flow function.

H_{0b}: Land cover indices do not affect stream flow indices, and are therefore not spatially limited.

H_{0c}: Hydraulic geometry is independent of catchment area within the Pee Dee watershed of South Carolina.

H_{0d}: Characteristic bed material is not influenced by any individual measures of stream flow function, stream geomorphology, or land cover.

While specific components of stream flow function, hydraulic geometry, measures of land cover, and characteristic bed material are elaborated upon later, the scope of the SCPDP and even this sub-study become apparent. The purpose of this study was to simply illuminate influencing factors on the stream system function for the eventual development of planned, state-regulated flow regimes (in this case, MAFs) that will maintain the geomorphological and ecological viability of the Pee Dee watershed; ultimately meeting human and ecological needs for years to come.

⁵ Components of Stream Flow Function in this study included Qualitative Habitat Evaluation Index (QHEI), bedload normalized by watershed area, Richards-Baker Flashiness (RBI), temperature variation, bankfull occurrences per year, and the Hammer Number. Each individual components are elaborated upon in the Methods chapter (Chapter 3).

2 LITERATURE REVIEW

Although the end-result is ideally simple, the route to a properly-developed MAF or EFR involves a web of numerous, interconnecting branches. These branches not only include physical, chemical, and ecological components of the river system, but account for anthropocentric need. Ideally, a properly developed MAF should satisfy both the preservation of the natural riverine system while meeting the requirements of humans. The following pages will provide a general overview of the considerations necessary in the development of a MAF and a much more detailed analysis of physical influences on stream dynamics.

2.1 RIVER HEALTH: CONTRIBUTING FACTORS

In order to attain the necessary information to properly plan an EFR or MAF, the many components of a river system, both physical and ecological, must be evaluated. Numerous studies have been conducted that attempt to define and quantify the ecological viability of a riverine system. These studies have sought to use indicators ranging from habitat (D'Ambrosio et al. 2009; Frimpong et al., 2005; Sponseller et al., 2001; Piégay and Gurnell, 1997; Rankin, 1989), to macroinvertebrates (Lecraw and Mackereth, 2010; Bunn and Davies, 2000; Menhinick, 1964), to fish assemblage (Clark et al., 2008; Kaufmann and Hughes, 2006; Magurran and Phillip, 2001; Paller et al., 1996; Fausch et al., 1984). Countless others have focused on physical and geomorphological parameters of a stream to characterize the stream condition, such as bed form and bed material (Jayakaran and Ward, 2007; Olsen et al., 1997, Copeland, 1994). Meanwhile, others have found measures of land cover to be indicators of both ecological and geomorphological degradation (Bedoya et al., 2009; Sponseller et

al., 2001; Wang et al., 1997, Schlosser, 1991). Others report that a degraded bed structure and habitat directly correlates to imbalances in the ecological system (Clark et al., 2008; Richards et al., 1996).

The culmination of these findings serves as invaluable insight into the management of streams as a whole. This has become increasingly apparent in many complex models that attempt to capture the complexity of riverine systems (Richter et al., 2003; Arthington, 1998; Thomas et al., 1996; Swales and Harris, 1995). Perhaps the single greatest commonality between all of these systems is their attempt to integrate and understand physical, chemical, and biological processes both within the riverine environment, and within the entire catchment.

2.2 WATERSHED SCALE ANALYSES AND STREAM HEALTH

It is a well-known-fact that anthropogenic changes to the landscape alter riparian systems (Brabec, 2009; Booth et al., 2004; Allan, 2004; Poff et al., 1997; Hammer, 1972). In many cases, these alterations surpass the system's ability to return to its original state. In fact, as much as 98% of North American prairie has been altered from its original state to accommodate modern agricultural practices (Blahn et al., 2009). In order to utilize land cover data for the analysis of riparian condition, spatial scale and specific land covers must be examined as a method of detecting the influential scales and land cover classes within a study area (Blahn et al., 2009; Sponseller et al., 2001).

2.2.1 The Effects of Land Cover Modification

Few can deny that land cover affects the riparian system by modifying the land's capacity to enhance pollutant removal from runoff associated pollutants such as nutrients, sediment, and water. Blahn et al. (2009) identified the *modification of hydrology, geomorphology, nutrient cycling, and sediment dynamics* as being major threats to riparian systems. Land cover changes can result in drastic changes in the water

quality (Bedoya et al. 2009), hydrologic regime (Booth and Jackson, 1997), or increase sediment inputs that subsequently impair stream habitat (Tufford et al., 2003; Gergel et al., 2002). However, such drastic changes often cannot be linked to a single common stressor (Bedoya et al. 2009).

Quantifying Anthropogenic Influence on the Landscape

There are many methods that exist that attempt to quantify anthropogenic influence on a landscape. Some of these include the analysis of Total Impervious Area (TIA) (Hammer, 1972), Landscape-Disturbance Indices (LDI) (Stanfield and Jackson, 2011), and developed land within a watershed. Each has been found to indicate to some degree the physical and ecological condition of the stream system (Brabec, 2009; Booth and Jackson, 1997).

Total Impervious Area (TIA) is a combined term of connected and isolated impervious area (Brabec, 2009). Total Impervious Area has been determined to have varying effects on the watershed (Brabec et al., 2002). However, there seems to be a threshold of TIA, as Schueler's (1994) review of available literature (before 1994) found a threshold of 10-15% imperviousness (TIA) in the watershed before the stream condition begins to show noticeable signs of decline. However, more recent reports have found threshold to be lower, ranging from 4-9% (Brabec, 2009; Baker et al., 2004; Hicks and Larson, 1997). Despite slight discrepancies in threshold, one finding rings true: above a certain threshold, increased TIAs result in degraded stream condition.

Landscape-Disturbance Indices are another way to simplify a landscape into a single measure. This involves the use of a weighting system where each land cover is assigned a number based on the amount of predicted amount of disturbance that has occurred to the landscape. Values are assigned between 0-1 and are multiplied by the fractions of the land cover that corresponds to them. These are then summed into a single metric used to describe the area of interest, such as a catchment or some sub-corridor of the stream. Water and wetlands are considered to have no landscape

disturbance (LDI=0) while the most disturbed areas could have a value of one (the highest found in literature was 0.9; Stanfield and Jackson, 2011)

Developed area, perhaps the easiest and most direct method of assessing a landscape change and its associated metric, urbanization, have been studied by (Pizzuto et al., 2001; Tufford et al., 2003; Booth and Jackson, 1997; Hammer, 1972). In fact Leopold (1968) stated “Of all land-use changes affecting the hydrology of an area, urbanization is by far the most forceful.” Evidence suggests that these changes are indeed forceful. Hammer (1972) found that urbanization and associated traits, such as sewage and storm drainage was linked to channel enlargement. Booth and Jackson (1997) found that impervious areas associated with urbanization resulted in decreases in aquatic function. Still others reported declines in the river form and function as the area in the watershed became more urbanized (Osborne and Wiley, 1988; Gergel et al., 2002; Allan, 2004).

2.2.2 The Analysis of Landscape at Multiple Scales

While some variables within a stream have localized/reach-scale relevance (such as species abundance), others are more important at larger landscape/watershed scales (such as species diversity, channel shape, discharge, etc.) (Bedoya et al., 2009). Landscape filters ranging from macro-to-micro scale habitats are also known to affect species diversity and populations, while anthropogenic filters (like dams) prevent fish and other biota’s movement and suitable habitat by altering upstream and downstream flows (Poff et al., 2006).

The spatial scale of such physical habitat assessments have also been evaluated on a basis of cost versus accuracy (Frimpong et al., 2005) with the intention of determining the most cost-effective scale for habitat analyses without sacrificing the accuracy of the results. Physical habitat assessments provide a key to the identification of historic alterations of landscape and flow (both anthropogenic and natural), current ecological stability, and provide insight into how to protect and restore the

riparian environment. For the most part however, habitat assessments remain feasible only at a reach-scale. However, Allan and Castillo (2007) found that it is important to assess the riparian system at a much larger scale than just a specific reach. Rather, several spatial scales should be incorporated into the assessment, ranging from microhabitat to whole-catchment. However, all spatial scales aren't equal, and it is vital to discern the importance of different scales in order to better manage the catchment area for the preservation of the riparian system. In a study by Allan et al. (1997), it was found that land cover tended to be a strong indicator of biological and habitat integrity for 100 m reaches, as determined by a habitat index (HI) and an index of biotic integrity (IBI). Agricultural land cover explained as much as 50% of the variance in IBI and 75% of the variance in HI, while the effect of land cover on variation in stream integrity was less pronounced. Also, Allan et al. (1997) showed that catchment-wide land cover data were far more indicative of biota and habitat than reach-scale land use, although correlations were found at both reach and catchment scales.

Although most habitat models simulate local phenomena such as velocity, in-stream fish cover, substrate, and condition at the reach scale (Frimpong et al. 2005; Wang et al. 2003; Allan et al. 1997; Roth et al. 1996; Berkman and Rabeni 1987; Oswood and Barber 1982), others have found these analyses to be scale dependent (Sponseller et al., 2001; Maddock 1999; Rankin, 1995). This is not to say that there is no merit in models limited to solely reach-scale analyses, but to highlight the importance of multiple scales in habitat analyses. As geographic information systems (GIS) have become more available and easy to implement, watershed-scale analyses can now be readily incorporated into riparian ecosystem analyses. In fact, multiple studies (McRae et al. 2004; Sutherland et al., 2002; Fitzpatrick et al., 2001; Davies et al., 2000; Stauffer et al. 2000; Richards et al. 1996) have shown that watershed-scale land cover data can be an accurate predictor of fish and invertebrate community data. Therefore, watershed-scale land cover can be used to assess stream health and ecosystem stability (Fimpong et al., 2005). The same goes for geomorphic condition,

which has been linked to agriculture, development, and impervious area within the entire watershed and at multiple scales (Sponseller et al., 2001; Pizzuto et al., 2000; Booth and Jackson, 1997; Hammer, 1972).

2.2.3 The Analysis of Modified Landscapes at Multiple Scales

Regional, catchment, and local-scale changes have varying effects on the biotic assemblages and riverine ecosystems (Richards et al., 1996). Some regional-scale factors are considered to be geomorphology, climate, hydrology, sedimentation, nutrient inputs and channel morphology while local scale factors are considered to be land cover and the analysis of local stream habitats (Hughes et al., 1994). Catchment scale can include a mixture of the previously mentioned parameters, as they can vary greatly in land area.

In a study in Michigan, Richards et al. (1996) separated land cover into two categories. Land cover factors, such as land cover and land fragmentation, aim to measure the amount of anthropogenic effects on a given land area. Landscape features include geological factors, such as soil type, slope, and catchment area, and generally have little or no anthropogenic influence (Richards et al., 1996). For land cover factors, Richards et al. (1996) used “urban, row-crop agriculture, non-row-crop agriculture, mixed forest, deciduous forest, herbaceous range land, shrubby range land, non-forested wetlands, and forested wetlands”. The study found that the larger spatial trends, such as biotic (in this case, macro-invertebrate) variation, tended to be more correlated to landscape features. Within the context of these larger spatial trends, small-scale trends seem to be just as apparent. Species variation was found to be very low in drainage areas with high levels (>85%) of row-crop agriculture. However, the most apparent indicator of ecological variation in Richards et al. (1996) was drainage area, a known influence of channel dimension and discharge (Dunne and Leopold, 1978). As

channel area increases, so does the species variability of macro-invertebrates and fish (Richards et al., 1997).

Similar studies have used similar divisions of scale. Sponseller et al. (2001) used 200 m, 1000 m, and 2000 m, and entire riparian reach buffers as well as whole catchment scales to investigate the influence of land cover on the riverine ecosystem. Sponseller et al. (2001) found that the selection of land cover scale was entirely dependent on the component of the stream being analyzed, where chemical variables tend to relate mostly to catchment-scale features, and biology and physical parameters of the stream tended to be most related to riparian-scale land cover features. From a watershed mapping standpoint, this method of partitioning the scale seems to be the most promising, especially when analyzing reaches smaller than 100 m become infeasible.

Land Cover

Hydro-modification for agricultural and other purposes falls into “two of the top threats to 135 imperiled freshwater fishes, crayfishes, dragonflies and damselfly, mussels, and amphibians in the United States” (Blahn et al., 2009; Stein & Flack, 1997; Richter et al., 1995). In fact, recent findings (Blahn et al., 2009) support the hypothesis that row crop agriculture has adverse effects on riparian systems (Wang et al., 1997; Roth et al., 1996; Richard et al., 1995).

The loss of wetlands, specifically as a result of agricultural drainage, occurs all across the United States, but is most prevalent in Ohio, Missouri, Illinois, Iowa, Indiana and California. Wetland loss has also been documented in parts of the Okefenokee Swamp in Georgia and parts of the Everglades in Florida (Blahn et al., 2009). This loss of wetlands contributes to a decrease in water quality, a direct loss or alteration of habitat, degradation of channel morphology through the loss of flood wave attenuation (Hillman, 1998), and adverse effects downstream (i.e. algal blooms, anoxic conditions, etc.) (Blahn et al., 2009).

More specifically, Blahn et al. (2009) highlight the effects of hydro-modification on the structure and function of stream systems. This is a well-warranted concern, as the drainage of agricultural land has been associated with nutrient input into natural systems (Alexander et al, 2000; Omernick et al., 1981).

2.3 REACH SCALE ANALYSES AND STREAM HEALTH

As the human influence on land and natural systems continues to grow, and river systems to change and adapt, it becomes all the more important to be able to predict and remediate adverse changes to the riverine system. More importantly, we should learn to prevent them. Perhaps Luna B. Leopold (1973) said it best in a closing address to the Geological Society of America:

“As suburban growth continues apace, its subtle and delayed effects on the river environment – rate of process, characteristics of channels and flood plains, sediment movement, and aesthetic values – are going to be affecting more areas and more people. In the small basin discussed here, the picnic places where I took my children are now muddy trash heaps. Where we played catch, there is now a shrubby and scrubby jungle. The little stream is littered with bricks, concrete trash, plastic bottles, and old tires. Nearby, new and expensive houses look out on a brown mudhole in a small silt-control basin constructed by the builder. If we are to devise ways in which urban development may proceed with a minimum of these adverse effects, we must have facts – observations made on the ground documenting effects of particular actions. Our present programs of river observation concentrate primarily on flow records and, much less intensively, on water-quality determinations. But the facts needed in the face of city growth go far beyond the network observations. We must begin to see the river as a whole – or reaches of a river unit. A river is far more than the water it contains. The information required is not necessarily complicated or costly. A few days of work a year can sustain a valuable observation program, if continued through a span of years. Yields can be both in theoretical knowledge of process as well as practical knowledge for design. Geologists, more so than most people, know how the natural world operates and what beauty lies in these mechanisms of nature. If some of the beauty of undisturbed processes is to exist within the reach of cities, the present practices of planning, design, and construction must include some geologic knowledge. That knowledge can only come from us.”

This was in response to a 20 year study, where Leopold had found that a stream in Rockville, Maryland now flooded as much as 5 times as often and the channels cross sectional area had contracted 13-20%, all as a result of rapid urbanization (Leopold, 1973).

Definitions of Necessary Terms:

Before continuing, it is necessary to define some terminology that will be used within this section of the literature review, and will continue to be used throughout.

Although there is an array of possible terms, for the sake of simplicity only a few will be discussed. The first is the concept of bankfull. Bankfull discharge has been defined as *the discharge that fills the channel to its active flood plain* (Leopold and Wolman, 1957). However, variations of this definition include the *flow at which a channel is filled to its banks* (Williams, 1978), *the height of the valley floor* (Nixon, 1959), or the *height of the lower level of perennial vegetation, typically surveyed as trees* (Bray, 1972), compiled from Radecki-Palek (2002). For the sake of clarity, however, Leopold and Wolman's (1957) definition will be adopted (the discharge that fills the channel to its active flood plain). In an effort to better define this *fuzzy* number (Johnson and Heil, 1996), Dunne and Leopold (1978) later outlined the following to be indicators of bankfull elevation:

- 1) *A topographical break from the vertical bank to the floodplain.*
- 2) *A topographical break from steep slope to gentle slope*
- 3) *A change in vegetation from bare-grass, grass-moss, or no trees-trees*
- 4) *A textural change in the deposition of sediment*
- 5) *The elevation below which no fine debris (needles, leaves, cones, seeds) occurs*
- 6) *A textural change between matrix material between cobbles or rocks*

An important, often associated term is effective discharge. Effective discharge is the range of discharges that are responsible for moving the most amount of sediment over time (Wolman and Miller, 1960). In a stable stream system, or one in *dynamic equilibrium* (Leopold, 1992), the effective discharge should be equal to bankfull discharge. However, in a system that is not in dynamic equilibrium, bankfull and effective discharge will differ.

Aside from the observational method mentioned above, other methods for the determination of bankfull depth have been defined but will not be covered in this document (Schumm, 1968; Wolman,

1955). Bankfull values of flow rate, width, depth, and area are all taken when the stream depth is at the determined bankfull elevation (see Figure 2.1).

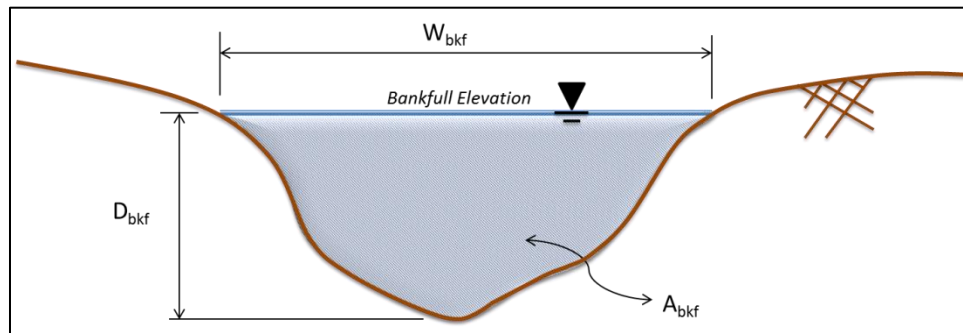


Figure 2.1 – Hypothetical representation of bankfull measurements, where the stream bottom is represented by a solid brown line and the water level in the channel is the determined bankfull elevation.

Stream pattern is another important descriptor of channel behavior. Stream pattern is characterized by stream sinuosity, which is defined as the curvilinear length of the river, measured along its centerline (L_m), divided by the straight length of the valley in the direction of slope (L_s) (Khatsuria, 2010). Therefore, the greater the sinuosity of the river, the more tortuous its course; the closer the sinuosity index approached unity, the straighter the channel.

With regards to sediment, D_{16} , D_{50} , and D_{84} are commonly used terms used to describe sediment size distribution. The subscript number that follows the D (“diameter”) indicates the percentile of the sediment size distribution that is smaller than a sediment size value. For example, if a D_{84} is found to be 2000 mm, this would indicate that 84% of the sediment distribution is smaller than 2000 mm in diameter. However, few particles are spherical. Rather, they must be characterized as having 3 dimensions, with the median diameter being the defining diameter. (This is logical because sieves, or screens, are often used to sort bed materials. In order for a particle to pass through a particular screen, 2 of its 3 dimensions must be smaller than the mesh size.)

Although the concept of slope is somewhat easy to grasp, it is important to recognize that there are 3 separate slopes for any given stream. These are bed slope, water slope, and energy slope. Bed slope

is the sloping trend line drawn through a series of points that define the river thalweg. Energy slope is the trend line drawn through the points that define the sum of potential and kinetic energy of the stream channel defined by Bernoulli's Equation (Cimbala and Cengel, 2008). In practice, energy slope and water slope are typically parallel and therefore synonymous (Gordon, 2004).

2.3.1 Stream Classification Systems

Many have tried to classify stream systems as a way to both interpret a stream's current condition and a way to better understand their response to certain changes, and as a result, four prominent classification systems have surfaced. This includes the Rosgen Classification of Natural Rivers, the USDA Forest Service Framework of Aquatic Ecological Units, the Channel Evolutional Model (CEM), and the Classification of Channel Reach Morphology.

Rosgen's Classification of Natural Rivers

Perhaps the most prominent and widely utilized classification system is the Rosgen Classification of Natural Rivers which analyzes current condition of a stream. This system was developed as a result of 30 years of fieldwork and observations of streams and rivers across America (USDA-NRCS⁶, 2006). Rosgen's classification system is based on bankfull discharge, which is dubbed "channel forming flow" due to its higher energy level (USDA-NRCS, 2006). This system is applied only along short stream reaches due to the dynamic nature of river systems, where even morphological features can change over short distances (Rosgen, 1994).

Besides being the most utilized stream classification method, this method holds value in its ability to be multidisciplinary (USDA-NRCS, 2006). Also, this method has been linked to suggested methods of restoration, possibly leading to more restorative processes and actions in the future (USDA-

⁶ United States Department of Agriculture – Natural Resource Conservation Service

NRCS, 2006). However, there are an array of shortcomings that need to be considered when using this method. The first is the grouping of silt and clay into a single classification of bed material, when silt and clay can have entirely different behavior in regards to multiple channel processes (USDA-NRCS, 2006). Other possible shortcomings include the lack of an upper limit for C and D stream types and that this method does not address variability in aggradation, degradation, and other rates of sediment movement along a stream reach (USDA-NRCS, 2006).

USDA Forest Service Framework of Aquatic Ecological Units

The main purpose of the USDA Forest Service Framework of Ecological Units (Maxwell et al., 1995) is to provide a consistent method of stream classification of stream systems at multiple spatial scales (USDA-NRCS, 2006). Perhaps the single largest advantage of this method is its versatility between classification systems, simply because of this system utilizes multiple classification systems within a single method. Once a stream has been classified using the USDA Forest Service Framework of Ecological Units, it can be translated to several other classification systems with little modification (USDA-NRCS, 2006). However, unlike the Channel Evolution Model, this system does not indicate evolutionary trends for different classes of stream reaches (USDA-NRCS, 2006).

Channel Evolutional Model

The Channel Evolution Model (CEM), developed in the 1960's, is a product of a set of streams that were channelized and observed over time. The result is a series of stages that all streams go through as a response to channelization (NRCS, 2006). These were classified as reach types I-V (Schumm, 1984) (see Figure 2.2).

In 1989, Simon revised the CEM to its more widely utilized version today (NRCS, 2006). In this revised CEM, he defined stream cross sections in five classes (1-5) and six types (I-VI). The *classes* in Simon's model correspond to Schumm's *patterns*. However, Simon's (1989) addition of stream types

is in reference to stream change and the stream evolution that occurs as means to reach dynamic equilibrium after a major stressor (such as human development within a watershed). While this method can accurately predict the next stage of a particular cross section in degraded channels or watersheds it cannot be applied to undisturbed channels or watersheds. Also, because this study was performed in an area where both the slopes and soil type were fairly uniform, it important that similar conditions exist for the application of the CEM. Another important condition would be that land cover does not significantly change, which would spark a new set of stages in the CEM. Assuming these conditions are met, the CEM is a powerful tool in both remediation and classification of streams current and future condition (USDA-NRCS, 2006).

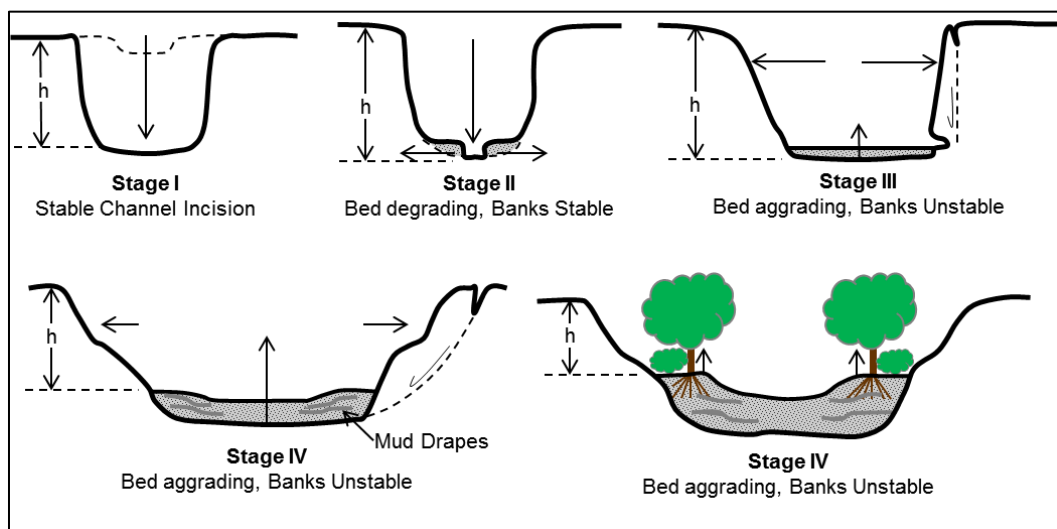


Figure 2.2 – Pictorial example of Schumm's (1984) Channel Evolution Model. Picture was adapted from http://www.ci.austin.tx.us/watershed/erosion_tech_engineer.htm

The mechanics of such incision can be simplified using Shield's equation (Shields, 1936) (Equation 2.1). This equation is used to calculate the shear stress needed to move a particle of bed material. The point at which a particle moves is directly proportional to the shear stress imposed by flowing water and inversely proportional to the particle diameter and the relative densities of the water and sediment. Within a given sand bed stream, particle densities stay relatively constant. Stream

temperature also remains relatively constant when compared between years, and so water density would remain relatively constant. Therefore, the component that changes with changes in flow rate is really shear force (τ), which is a function of flow velocity and flow depth. If the typical value for the incipient motion of a particle with diameter D_{50} , and shear stress τ , is known to be τ_{θ}^* (or 0.047), then as shear stress increases as a result of increased τ (i.e. an increase in velocity and depth), then D_{50} will increase as greater shear stresses imparted on the bed start to move larger particles (Julien and Wargadalam, 1995).

$$\tau_{\theta}^* \approx 0.047 = \frac{\tau}{(\rho_s - \rho)gD_{50}} \quad (2.1)$$

Where τ_{θ}^* (dimensionless) is the shields parameter associated with incipient motion, τ is shear stress at the particle-fluid boundary, ρ_s is the density of the particle, ρ is the density of the fluid, g is the gravitational constant, and D_{50} is the characteristic (Shields, 1936) or median grain size.

Classification of Channel Reach Morphology.

Like Schumm's (1984) CEM, Montgomery and Buffington (1997) sorted alluvial channels into 5 classes. These classifications include, cascade, step pool, plane bed, pool riffle, and dune ripple. Step pools and cascades typically occur in steeper slopes, while the remaining 3 alluvial classes occur at milder slopes, typically well downstream.

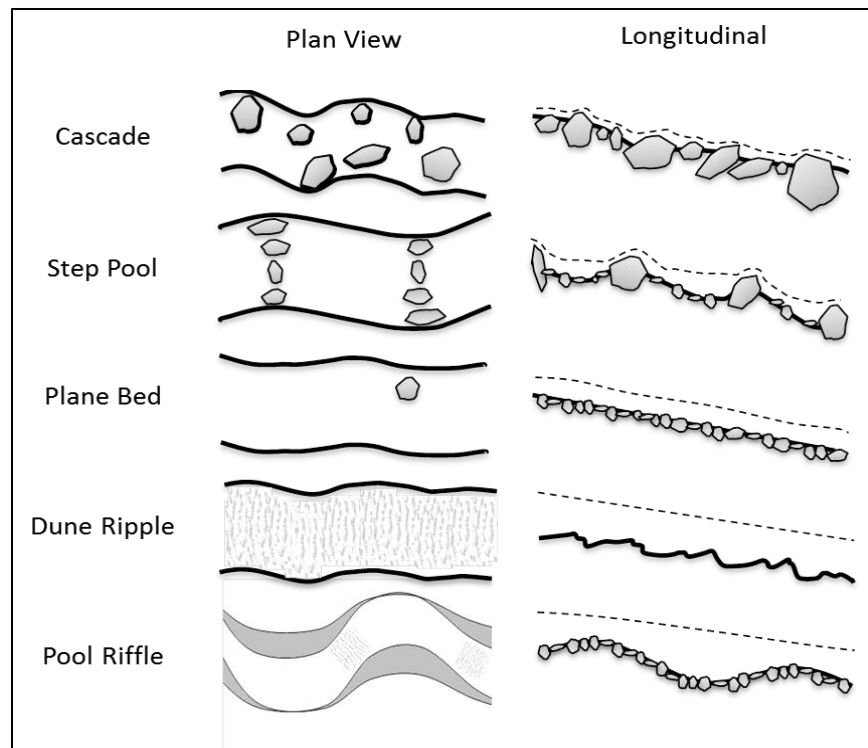


Figure 2.3 – Plan and longitudinal view illustrations of Channel Reach Morphology stream classes (adapted from Montgomery and Buffington, 1997)

While Figure 2.3 may suffice for general characterization using Montgomery and Buffington's method, a more detailed look at the identification and implications of these classifications can be referenced in Montgomery and Buffington (1997). The Classification of Channel Reach Morphology also highlights the locale of a particular stream reach being of utmost importance when considering sediment loads, especially in regards to sediment balances over time. Montgomery and Buffington (1997) state that while it is thought that most streams should maintain a sediment flux that is balanced, some stream reaches will normally have a negative net sediment loss (e.g. high gradient mountain streams) while other stream reaches tend to accumulate sediment (e.g. low gradient reaches at the base of mountainous regions). However, streams at the base of a high gradient system, where slope and energy are significantly reduced, actually will tend to have a net sediment gain. In alluvial channel classifications, only Cascade and Step Pools fall into the category of sediment loss, and

where classified as *transport reaches*. Meanwhile, Plane Bed, Dune Ripple and Pool Riffle alluvial channels, where net positive sediment flux tends to occur, were called *response reaches* (Montgomery and Buffington, 1997).

Montgomery and Buffington's (1997) classification system seems to encompass many of the types of alluvial channels through the lens of a geomorphologist, and they added one critical consideration: large woody material (LWM). Large woody material has the ability to drastically affect streams and rivers by forcing their morphology. Although the effect is more profound in streams where LWM length exceeds channel width, larger streams and rivers can be have forced geomorphology due to log jams. Although not always present, LWM is an important consideration when defining a river or stream reaches geomorphic class (Montgomery and Buffington, 1997).

The Channel Reach Morphology is an explicit and accurate method of stream classification, but there are several considerations that should be accounted for before relying solely on Classification of Channel Reach Morphology. The first is that this is a geomorphic approach to river classification. As a result, adequate training and understanding of the system should be used when those other geomorphologists are utilizing this system. The second, and probably the most important, is that this method was defined for Northwestern United States mountain systems. Therefore, when applying Montgomery and Buffington's Classification of Channel Reach Morphology to other geographic areas, care should be taken to account for differences in local topography. (USDA-NRCS, 2006)

2.3.2 Regional Trends in Channel Geometry

The existence of similar hydraulic geometry (width, depth, area, and flow rate) in streams with topographically similar watersheds is well documented and referred to as hydraulic geometry, or regional curves (Metcalf et al., 2009; Sweet and Geratz, 2003; Leopold, 1994; Dunne and Leopold, 1978). Regional curves developed for various areas are generally represented in the form of a power

equation ($X=kY^d$), as in Dunne and Leopold (1978). While Dunne and Leopold's (1978) regional curves relied on a bankfull flow rate (Q_{bkf}) as the independent term of a power relationship of the form $W_{bkf}=aQ_{bkf}^b$, recent studies (Metcalf et al., Cinotto, 2003; Sweet and Geratz, 2003; Doll et al., 2002; Castro and Jackson, 2001) have since adopted catchment area (A_c) as the independent term ($W_{bkf}=aA_c^b$). This replacement of bankfull flow rate by catchment area is supported by the well-documented relationship between watershed area and bankfull flow rate (Doll et al., 2002; Castro and Jackson, 2001). The conversion from Q_{bkf} to A_c was fueled by the emergence of efficient desk-top mapping software and GIS (e.g. ArcView®, ArcMap®). This is a resource-efficient method when compared to field measurement, which involves the cost and time of 2 surveyors traveling to and from the site as well as the cost of the associated equipment. As a result of this widely-adopted conversion, (Metcalf et al., 2009; Cinotto, 2003; Sweet and Geratz, 2003; Castro and Jackson, 2001), it may be necessary to adapt past studies (e.g. Leopold, 1994; Hey and Thorne, 1986) and regional curves to the new standard. The analysis of regional curves have been separated by regions, including ecoregion (Sweet and Geratz, 2003; Castro and Jackson, 2001), physiographic province (Metcalf et al., 2009; Cinotto, 2003), and the incorporation of average annual rainfall and runoff patterns (Metcalf et al., 2009). It is not recommended that curves be extrapolated beyond their respective study areas, as regional curves tend to vary dramatically between study regions (Refer to the differences in regional curves found in: Metcalf et al., 2009; Jayakaran et al., 2005; Sweet and Geratz, 2003; Doll et al., 2003; Castro and Jackson, 2001; Leopold, 1994; Hey and Thorne, 1986).

2.3.3 Sediment Flux and Stable Channel Analysis

Sediment flux is an important consideration in determining the state of the stream. In particular, the question of whether or not the sediment flux is balanced at upstream and downstream reaches. If the stream is not transporting the supplied sediment, sediment is being deposited in the reach under study resulting in an aggrading stream. If the downstream reach is transporting more than the

available sediment, then the stream is effectively exporting sediments from the channel bed and banks and is therefore said to be degrading. If the sediment supplied is equal to the sediment transported (i.e. neither aggradation nor degradation is occurring), then the stream is said to be in a state of *dynamic equilibrium* (Leopold, 1992).

An Empirical Method for the Determination of Bedload Flux

Although bedload can be measured, it is a time and resource intensive exercise, requiring frequent monitoring and measuring of sediment traps or sediment benchmarks. This complexity has encouraged the development of empirical methods that can estimate the bedload flux of a particular reach based on more easily-measured variables such as flow rate and substrate character.

One method in particular, Brownlie's (1981) transport and resistance equations (outlined in the NRCS engineering handbook, 2006) holds particular promise for sand bed channels, with bed material D_{50} ranging from 0.04-29 mm and 0.08-28 mm. This method can be used to determine the amount of sediment that a channel used based on channel dimension, median bed material size (D_{50}) and gradation coefficient.

The Larson Transport Function and Channel Stability

By using the analytical method known as the Larsen transport function, developed by Copeland (1994), a range of each width, slope, and depth of a stable reach can be determined based on flow rate, sediment inflow, and components of bed material from an upstream reach (D_{50} and gradation coefficient). This analytical method allows for the comparison of an [upstream] stable reference reach to an actual reach for the classification of its stability (i.e. aggrading, degrading, or dynamic equilibrium), as well as an indication of what steps could be taken to help achieve dynamic equilibrium once again. Not only can this function be used for the redesign of a channel, but it can be used as an assessment of channel reach for its stability, and perhaps a degree of its stability. If a

width-slope-depth solution falls in the range of possible stable channels, then the channel is stable.

Otherwise, the channel reach can be classified as aggrading or degrading based on the comparison of the reach dimensions to the computed ones. However, this entire process requires a stable reach as to enable the quantification of bed load input, and the calculation of these stability curves.

Copeland's (1994) Larson function and stability curves are covered in greater detail in Appendix A3.

3 METHODS

3.1 SITE SELECTION

This project was limited to a study area within the Lower Pee Dee watershed in South Carolina.

Streams and tributaries within the lower Pee Dee exhibit relatively variable stream types, slopes, and watershed sizes, but can generally be classified as low gradient coastal plain streams with bed substrates that are a sand or sandy-gravel mix. Study sites were selected to represent a wide range of watershed drainage areas, ranging from 7 to 665 square miles.

Within the subcategories of small (<10 mi²), medium-small (10-50 mi²), medium (50-500 mi²), and large (>500 mi²), strategic use of United States Geological Survey (USGS) and South Carolina Department of Natural Resources (SCDNR) sites were selected to maximize project resources. Six USGS sites and five SCDNR sites were chosen of the 16 sites to be selected. As many as 20 additional sites were chosen ranging from 5 mi² to 1000 mi² of which six were chosen. The selection process evaluated each possible site on the basis of land cover within the watershed, ease of access, projected foot traffic (security), and wadeability.

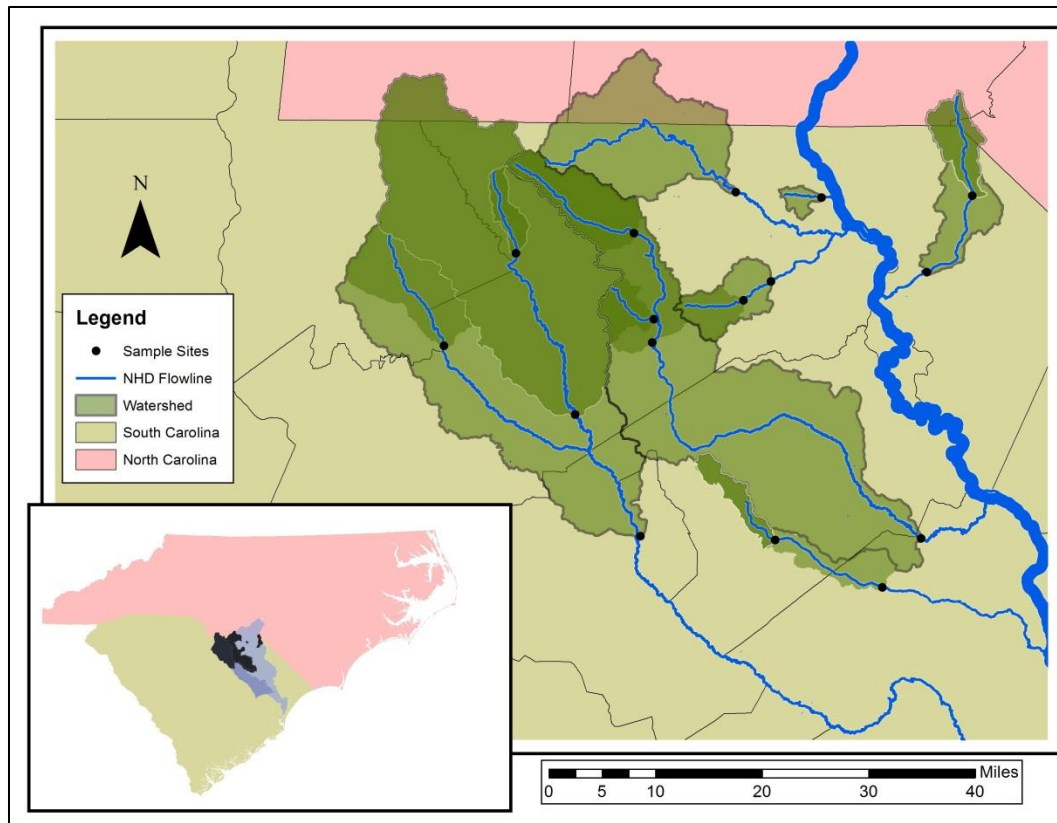


Figure 3.1 – SCPDP sites and watersheds overlaid on North Carolina and South Carolina county maps. The wide-view box in the lower left corner of the figure includes the Pee Dee and Lynches River watersheds, labeled with lighter and darker shades of green, respectively.

After the selection of the six additional sites, exact location of the monitoring equipment at the SCDNR and Clemson sites were determined based on the location of a permanent structure within a stream pool. This would not only ensure the security of the equipment, but would also ensure that the device experienced lower relative velocities than it would in a riffle of the same flow, as well as the maintaining a pressure head above the sensor at all times. Bridge pilings and road crossings were avoided when at all possible, due to the impeded flows and adjusted channel geometry caused by these permanent structures. Also, the site selection was influenced by a visual stream survey of the area, identifying a location where minimal flow obstructions occurred for approximately 300 feet both upstream and downstream.



Figure 3.2 – Example of stage recorder placement at Juniper Creek (DNR). The stage recorder is in the area highlighted by the yellow circle and the area highlighted in red represents the pool. Notice the amount of woody material present in the stream channel, this being one of the least debris ridden areas found.

3.2 LANDSCAPE ANALYSIS

3.2.1 Data Sources

Sources of data for landscape analysis came from several government agencies including the United States Environmental Protection Agency (US EPA), United States Geological Survey (USGS), and National Resource Conservation Service (NRCS). Land cover data was downloaded at a 30 m X 30 m resolution from US EPA in the form of the 2006 National Land Cover Dataset (NLCD). Digital elevation models (DEM) were downloaded from USGS geospatial data gateway at the same resolution. A higher resolution was available for some portions of the lower Pee Dee watershed. However, gaps in available data resulted in the decision to use the seamless 30 m X 30 m DEM. The USGS geospatial gateway also was the source of the National Hydrography Dataset (NHD). Soil data was downloaded through NRCS Soil Survey Geographic (SSURGO) Database. All layers were imported into ArcMap 10® (esri, 2010) for processing and analysis.

3.2.2 Watershed Delineation

Each watershed was delineated based on the point coordinate for each stream sampling and monitoring. For this analysis, a *filled* DEM was used as the Watershed tool input. The Fill tool

within the Hydrology Toolbox was used to perform the fill function and output a filled DEM. The watershed delineation tool was initialized (utilizing the filled DEM) and a relatively high Hydrologic Unit Code (HUC) value was used (typically between 12 and 16, depending on the size of the watershed). In nearly every case, the sampling point did not fall on the boundary of a sub-watershed, and so this watershed was trimmed based upon the DEM and NHD using a visual approach based on high points of elevation. When the sample point fell on a watershed boundary, the NHD was laid over the watershed boundaries and all watersheds upstream of the sampling point were merged into one layer.

Watershed polygons were used as clipping geometry for each of the other datasets, including DEM, NLCD, NHD, and SSURGO, resulting in specific watershed clips of each. This was a useful way of partitioning the comprehensive datasets into more manageable and useful pieces.

3.2.3 The Derivation of a Riparian Buffer

For the derivation of the riparian buffer, two layers were needed: the entire NHD layer and the DEM datasets for the lower Pee Dee watershed. The NHD was first converted from a polyline (shape layer) to a raster where all stream values were dedicated as 0 and all other values were dedicated as 1. Next, the DEM was filled, as discussed before. The Map Algebra tool (found in Arc GIS® Spatial Analyst) was then used to *burn* the stream into the DEM. The resulting was DEM essentially assigned an elevation of zero to all stream pixels. In this way flow *to* the stream was isolated from flow *in* the stream by essentially forcing water to stop once it reached the stream.

Next, flow direction was determined by using the Flow Direction tool (found in the Hydrology Toolbox) was used on the filled and burned DEM. Using the flow direction raster, the Flow Length tool was initialized, leaving all defaults. The output resulted in a raster where each pixel had a value that represented the flow length water would have to flow from that pixel (over the DEM surface) to

reach the stream channel. Values ranged from 0 to 9000 where 0 represented a pixel within the stream and 9000 represented a pixel with a flow length of 9 km from a stream system.

To get a buffer immediately surrounding the stream, a value of 180 m was chosen as a threshold value. The flow length raster was then reclassified so that any value greater than 1800 had a NULL value and all values equal to or less than 180 were reclassified to 1. The resulting raster was clipped by the watershed polygons (derived previously) as clipping geometry.

3.2.4 Flow Distance within the Stream and Classified Riparian Buffer

Once the stream buffer had been created, a distance upstream of the sampling site and towards the watershed divide had to be classified. Using the clipped DEMs, each DEM was filled and the same process of flow direction and flow distance was repeated, yielding again, a flow length raster. This raster showed a flow distance to the sampling point rather than simply to the stream as was the case previously. Using this Map Algebra, the resulting raster and the reclassified stream buffer raster were multiplied together to yield a raster that had flow length values to points solely within the riparian buffer. Finally, this raster was reclassified based on flow distances prescribed by Sponseller et al. (2001) who determined that certain flow distance class intervals were of particular significance in the context of environmental flows. These were 200 m, 1000 m, 2000 m, and entire riparian buffer as classified upstream of the sampling point. The four scales of analyses are defined as *200 m*, *1000 m*, *2000 m*, *entire buffer* as well as a *catchment* scale. The raster was reclassified to be 1000, 2000, 3000, and 4000, corresponding to 200 m, 1000 m, 2000 m, and entire buffer regions, respectively. These reclassified pixels were added to the 2006 NLCD land classification raster (with values ranging from 11 to 95) or CN (with values ranging from 25 to 100) using the Map Algebra tool. This allowed for the easy identification of both scale and land class (or CN). For example, a pixel labeled as 3011 would be within the 2000 m buffer (pixels in the 2000 m buffer were classified with a pixel value of

3000) and primarily open water (open water in the 2006 NLCD map was classified as 011).

However, in order to account for all open water land cover within the 2000 m buffer, subsequent values within the 1000 m and 200 m (coded 2011 and 1011, respectively) would be summed raster code 3011. The resulting raster, with overlaid NHD, resulted in something similar to Figure 3.3.

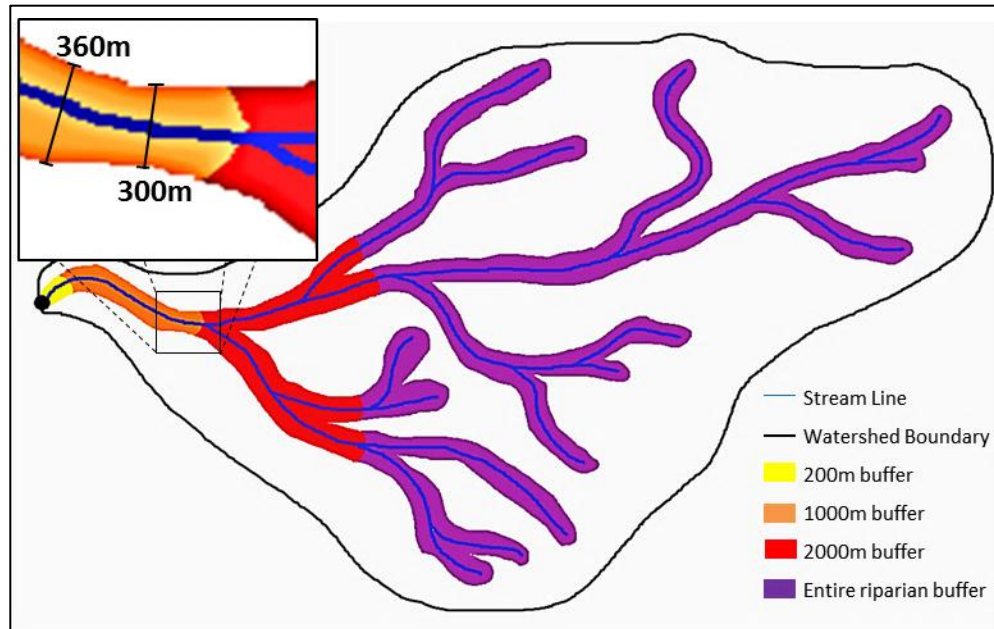


Figure 3.3 – Example of resulting classified stream buffer. Each color represents a different flow distance of the riparian buffer from the sampling point, with each larger flow distance including all that precede it. For instance, the 1000 m buffer would include the 200 m buffer as well.

In Figure 3.3, the sampling point (the black dot) would lay at the downstream most tip of the yellow section, the yellow represents the 200 m flow length within the 180 m riparian buffer, the 1000 m flow length would include both orange and yellow, 2000 m of flow would include all of the red, orange and yellow, and the entire buffer would be the entire colored buffer pictured. The entire catchment would be all land that fell within the black boundary.

3.2.5 Land Use, Curve Number, and Land Disturbance Index

The entire catchment land cover attribute table was exported to a spreadsheet program. For land cover within each flow distance of the riparian buffer, each clipped classified buffer was added to the NLCD layer using Map Algebra, yielding only values within the watershed buffer. These layers were also exported to a spreadsheet program for analyses of land cover classes within the 200 m, 1000 m, 2000 m, entire buffer and at the catchment scale.

Imperviousness of the landscape

The percentage of impervious areas in the study catchments were analyzed similarly to how of land cover classes were classified (previous section). Imperviousness maps generated from the USGS seamless website⁷, with pixel values ranging from 0-100 (percent impervious). Only *Total Impervious Area* (TIA), or “the fraction of a watershed covered by built surfaces or built ground” (Booth et al., 2004), was used in this study. Although TIA holds promise, it is important to recognize its shortcomings. Perhaps the greatest shortcomings are the omission of pervious surfaces that have been compacted (and therefore act as impervious surfaces) and its incorporation of isolated surfaces (Booth et al., 2004).

The determination of curve number

Curve number was found by classifying the various soil types in the SSURGO dataset by their hydrologic soil group (HSG) and combining them with land cover data. HSGs are denoted by A, B, C, and D, as well as A/D, B/D, and C/D, where the first letter represents how the soil behaves when it is drained and the second letter represents how the soil behaves when it is undrained (Haan et al, 1994). For example, HSG A will have a much higher conductivity when drained, but may act very similar to HSG D, hydraulically, when saturated. For this study, it was assumed that the soil was

⁷ seamless.usgs.gov/

drained, leaving only the classes of soils as A, B, C, and D. However, rasters must have a value in each cell and not a letter. Therefore, the same HSGs were set to 1000, 2000, 3000, and 4000 for HSGs A, B, C, and D, respectively. Using Map Algebra, HSG and NLCD layers (classified as numbers 11-95) were added using map algebra. These values were then reclassified as their corresponding Curve numbers (CN) shown in Table 3.1.

Table 3.1 – NLCD raster code (2006), classification (2006), and corresponding Curve Number.

Raster code	NLCD Land Class	Hydrologic Soil Group			
		A	B	C	D
11	Open Water	100	100	100	100
21	Developed, Open Space	44	65	76.5	82
22	Developed, Low Intensity	51	68	79	84
23	Developed, Medium Intensity	55.5	71	80.5	85.5
24	Developed, High Intensity	69	80	86.5	89.5
31	Barren Land (Rock/Sand/Clay)	72	82	87	89
41	Deciduous Forest	25	55	70	77
42	Evergreen Forest	25	55	70	77
43	Mixed Forest	25	55	70	77
52	Shrub/Scrub	45	66	77	83
71	Grassland/Herbaceous	30	58	71	78
81	Pasture/Hay	53.5	70	80	84.5
82	Cultivated Crops	62	71	78	81
90	Woody Wetlands	35	60.5	73.5	80
95	Emergent Herbaceous Wetlands	35	60.5	73.5	80

(*All values adapted from Haan et al., 1994)

Once all values had been reclassified to their respective curve numbers, Map Algebra was used to add the CN layer to the flow length to point. (Recall that the flow length to point had been reclassified earlier to have values of 1000, 2000, 3000, and 4000, for 200 m, 1000 m, 2000 m, and entire buffer flow lengths, respectively). Attribute tables were exported for both the entire CN layer and classified buffered CN layer, resulting in CN analysis at 200 m, 1000 m, 2000 m, entire buffer, and entire

catchment scales. Once the text files were imported, each scale was analyzed at as an average CN as well as % of CN above the 77 and 89 thresholds, which were CNs indicative of developed land.

The summary of land cover through the a Land Disturbance Index

Land Disturbance Index (LDI) was classified similar to those methods found in Morrison et al. (2006). This was simply the sum of the products of percentage of land cover and LDI factors (see Equation 3.1).

$$LDI = \sum_i (\% \text{ Land Use}_i \times LDI \text{ coefficient}_i) \quad (3.1)$$

However, to arrive at the same classification system used in Stanfield and Jackson (2011), some necessary simplifications of the 2006 NLCD dataset had to occur. The LDIs and 2006 NLCD dataset simplifications are summarized in Table 3.2.

Table 3.2 – Conversion from NLCD 2006 land class to Stanfield and Jackson (2011) LDI values

Stanfield and Jackson (2011) Land Classification	Corresponding NLCD Class (2006)	Stanfield and Jackson (2011) LDI coefficient
Wetland and open water	Open Water, Woody Wetlands, and Emerging Herbaceous Wetlands	0.00
Forest	Deciduous, Evergreen, and Mixed Forests	0.01
Open tallgrass Prairie	Grassland/Herbaceous	0.02
Idle land, thicket/meadow	Shrub/Scrub	0.10
Unimproved hay/pasture	Pasture/Hay	0.15
Manicured Open Space	Developed, Open Space	0.16
Open sand, dunes, orchards, vineyard	Barren Land (Rock/Sand/Clay)	0.20
Mixed Agriculture	Cultivated Crops	0.25
Rural/estate residential	Developed, Low Intensity	0.50
Urban Imperious (subdivisions/institution)	Developed, Medium Intensity	0.75
Transportation, industrial, commercial, rail	Developed, High Intensity	0.90

3.3 HYDROLOGIC MONITORING

Flow stage was measured using a self-contained stage recording sensor (Level logger Gold®, Solinst, Ontario). The sensors measure absolute pressure requiring measured data to be compensated for atmospheric pressure. Changes in atmospheric pressure were measured using continuously logging independent atmospheric pressure sensor (Barologger Gold, Solinst, Ontario). Atmospheric pressure was recorded at 3 sites distributed throughout the study area. Atmospheric pressure recording sensors were suspended well above the bankfull depth to ensure that they remain dry in all flow conditions.

Determining the level of the stage recorder relative the stream

The elevations of the water surface and channel bed at the location of the installed stage recording sensor as well as the time of measurement was determined using a total station⁸. This process defined the position of the stage sensor above channel bed, and therefore allowed for the determination of what the true depth of water in the channel was for any given stage sensor reading.

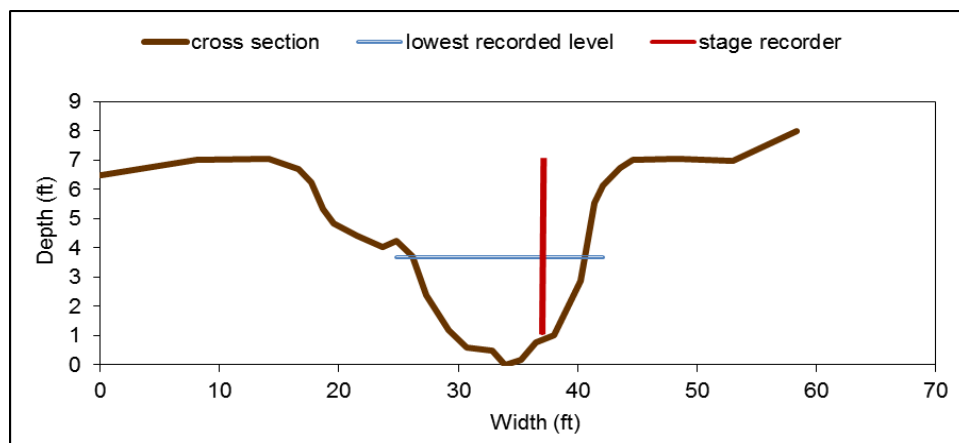


Figure 3.4 – Positioning of stage recorder in the cross section of Juniper Creek (DNR). The level of the water in this figure represents the lowest level recorded in the 2-year period of record.

⁸ Common in current surveying practices, the total station is a device that is an electric theodolite coupled with an electronic distance meter (Kavanagh and Bird, 1996). The end result is a very accurate reading of distance and direction between the total station and the surveyed point.

Data collection

Collection of data occurred every 2-3 months, where each data logger lost no more than 2, 10-minute data points in time and all logger data was collected within a 2-day period.

Once a complete dataset was downloaded, the water level data at each site was compensated for atmospheric pressure with data from the most proximal atmospheric pressure sensor. After compensation, the data was then exported to an Excel file for analysis.

3.4 STREAM GEOMORPHOLOGY

Three aspects of stream morphology were quantified in this study. These included stream *dimension*, *profile*, and *pattern* (Ward and Trimble, 2004). Stream dimension is the detailed cross-sectional measurement of the stream, well into the active floodplain. Stream profile is the longitudinal measurement of the stream bed in the direction of flow. Stream profile measurements help to characterize the undulations in the stream bed (riffle-pool complexes) as well as characterize water slope and therefore estimated energy slope of the stream. Stream pattern measurements are obtained concurrently with stream profile measurements and characterize the planform shape of the stream. Stream sinuosity is typically calculated from stream pattern information. An example of a dimension, profile and pattern from a single stream can be found in Figures 3.5a-c.

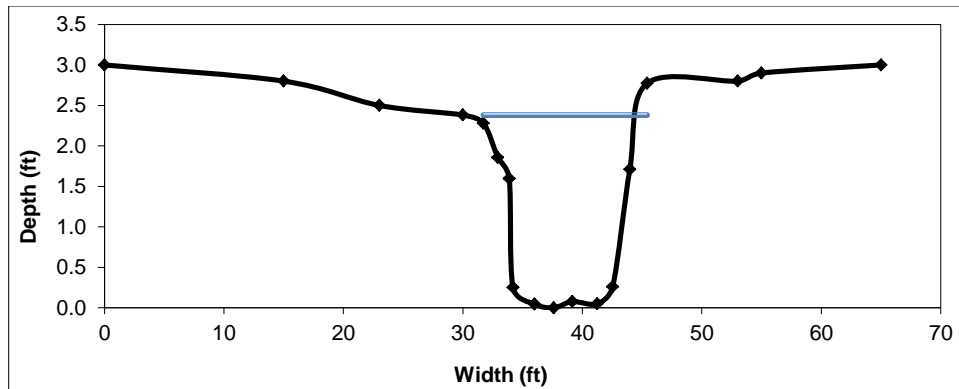


Figure 3.5a – Cross section from Huckleberry Branch. Each point represents a measured value while the line is interpolated between each two points. The horizontal blue line represents the projected bankfull based upon channel geometry and in-field observations.

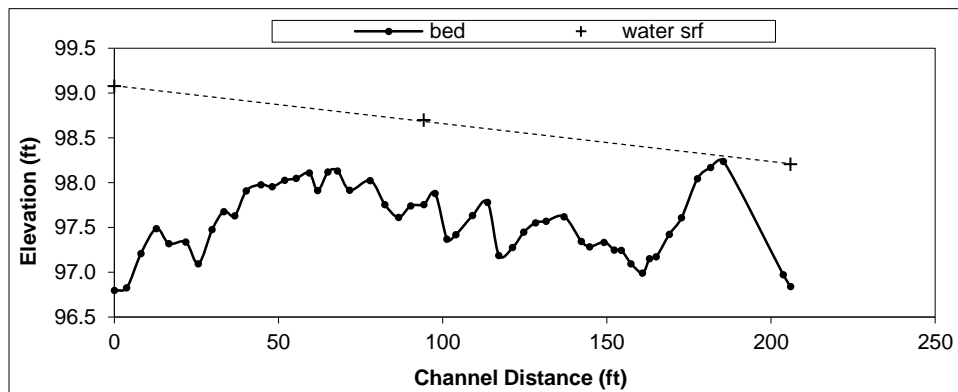


Figure 3.5b – Profile data from Huckleberry Branch. The “+” marks represent the measured water level and the dotted line represents the interpolated water slope. The points on the bed profile are measured values and the solid line is the interpolated bed value.

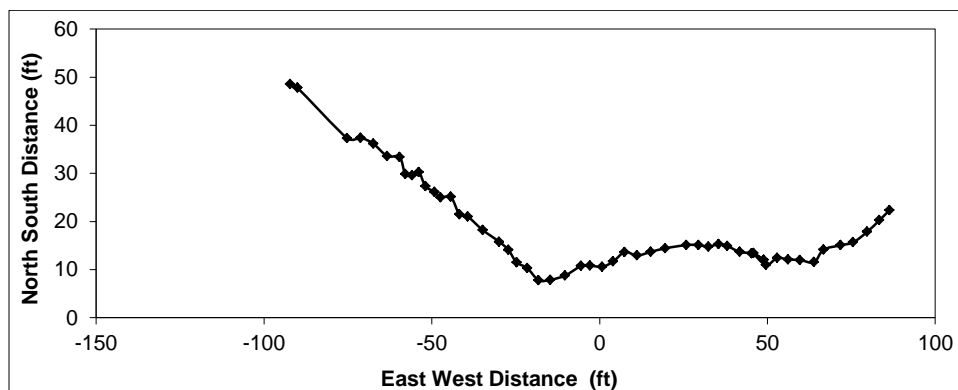


Figure 3.5c – Planview of the surveyed section of the stream from the profile data of Huckleberry Branch. Each diamond represents a data point while the line has been interpolated for the visualization of the plan-view.

Four types of equipment were used for the measurement of these parameters, including a total station, a Sontek RiverSurveyor S5⁹, and a Sontek RiverSurveyor M9¹⁰. Both Sontek® (YSI, San Diego, CA) instruments are floating Acoustic Doppler Current Profilers (ADCP) that measure channel bathymetry and flow velocities within the stream by tracking individual particles in stream flow as they pass underneath the floating ADCP. The ADCP also tracks the bottom, and so as is slowly moved across the stream, the reported average particle velocities are relative to the ADCP positioning over a point on the bed.

3.4.1 Surveying Wadeable and Nonwadeable Streams

Stream pattern, dimension, and profile were measured using one of two methods. In wadeable streams, a total station was used across a cross section and into the floodplain. As many as 50 data points were taken across the cross section, taking careful note of indicators of bankfull level (including geometric changes, changes in vegetation, significant changes in particle size, level of organic debris, or scour lines (outlined in Dunne and Leopold, 1978)), floodplain, and thalweg within and around the stream. Otherwise, the process is outlined in USDA's Illustrated Guide to field technique (Harrelson et al.; 1994) in Appendix 6 under the subtitle "5. Surveying Basics."

The second method, used in the nonwadeable streams, utilized the Sontek RiverSurveyor[®] S5/M9. Differences between the S5 and M9 models include the number of transducers (5 and 9, respectively), the depth range of velocity profiling (5 m and 40 m, respectively), and range of the bottom depth measurement (15 m and 80 m, respectively), with no difference in accuracy or resolution. This method required 2 ropes that were more than the width of the stream channel. The ADCP was slowly pulled along the length of the cross section, keeping tension on the rope from

⁹ A floating Acoustic Doppler that measures water velocities as well as stream dimension.

¹⁰ An upgraded version of the Sontek RiverSurveyor M9, this equipment integrates RTK differential GPS for precise measurement of stream profile in addition to its predecessor's (S5) features.

both sides. The velocity of the RiverSurveyor perpendicular to flow never exceeded one tenth of the water velocity. Once reaching the opposite bank, the file was saved and the instrument repositioned and re-initialized to be pulled slowly back across the stream. This process was repeated until three cross-sectional flow readings were with +/- 1% of each other.

3.4.2 Stream Profile: Water Surface Slope and Energy Slope

Stream profile was surveyed using the total station or RiverSurveyor M9 for wadeable and nonwadeable streams, respectively. When using the total station, readings of water surface, thalweg, and bankfull height were all taken along multiple cross sections along a length of the stream, as per Harrelson et al. (1994). The River Surveyor M9 was used on all nonwadeable streams and dragged a distance of at least 30 times the bankfull width using a small raft and trolling motor. Slope could only be accurately measured once both the RTK unit (the stationary GPS unit) and the RiverSurveyor had established RTK-quality GPS and established a connection with each other. In some cases, this resulted in only a few acceptable points in space (Real-Time Kinematic GPS accuracy of longitude, latitude, and elevation). The drop in elevation, in combination with the curvilinear distance of the stream, was used to determine the average water slope within a given cross section using the equation below:

$$S = \frac{|Z_u - Z_d|}{x} \quad (3.2)$$

Where S is the slope (ft/ft) Z_u is the upstream absolute elevation (ft), Z_d is the downstream absolute elevation (ft), and x is the curvilinear distance of the stream (ft).

3.4.3 The STREAM Module

All data was imported into Excel from the total station using Matlab® and RiverSurveyor Live® software for the RiverSurveyors. When the laser level was used, these values were transferred from field data sheets to Excel, manually. All values were then imported into the macro-enabled Reference Reach Spreadsheet for Channel Survey Data Management (a STREAM module), developed by Mecklenburg and Ward with Ohio Department of Natural Resources (2004). This spreadsheet aided significantly in the determination of slope at many sites as well as in the determination of bankfull conditions through the easy adjustment of the depth parameter with outputs including bankfull width, depth, and area, among others.

Determining Bankfull

Bankfull elevation was determined based upon visual estimates of Dunne and Leopold's (1978) indicators of bankfull elevation. These included a *topographical break from the vertical bank to the floodplain; a topographical break from steep slope to gentle slope, a change in vegetation from bare-grass, grass-moss, or no trees-trees; a textural change in the deposition of sediment; an elevation below which no fine debris (needles, leaves, cones, seeds) occurs; and a textural change between matrix material between cobbles or rocks.* The determination of bankfull is inherently *fuzzy* (Johnson and Heil, 1996) due to the dynamic nature of streams. Gorden et al. (1992) identify four possible sources of such fuzziness, including instability, non-level floodplains, terraced streambeds, or simply the lacking of any defining features or clear breaks between channel and floodplain. As a result, it must be emphasized that the resulting determination of bankfull depth, and subsequently all other bankfull values, were estimates, albeit estimated according to Dunne and Leopold's (1978) original bankfull elevation determination guidelines.

3.5 FLOW DETERMINATION

The measurement of flow rates was also dependent on the stream size. For nonwadeable streams, the use of the RiverSurveyor S5/M9 yielded flow rates for a given cross section, as well a highly detailed velocity profiles within the water column. In wadeable streams, a Sontek Flow Tracker® (YSI, 2009) was used to measure velocities across a measured cross section. The probe was placed at 60% of the water height (for most wadeable streams), and a measurement was taken at half-foot increments across the wetted cross-section. The method followed for velocity measurements can be found in John (2001). These velocities were combined using a weighted average across a cross section to determine a weighted average velocity (V_{ave}).

In both cases, a single discharge for a single stage was recorded for each site. Using Manning's Equation (Gauckler, 1867), the variables can be rearranged to calculate n .

$$n = kV_{ave}R_h^{2/3}S^{1/2} \quad (3.3)$$

Where k is a conversion constant¹¹, n is Manning's roughness coefficient, V_{ave} is measured average velocity, R_h is hydraulic radius¹², and S is slope (length/length). Once this single n -value had been defined, it was assumed that this value was representative of the entire channel and therefore constant until bankfull conditions are exceeded. This assumption makes it possible to calculate a stage discharge curve from only one stage measurement.

The stage discharge curve was developed by using Manning's Equation and the continuity equation ($Q=VA$) using 0.01ft stage increments at each site.

$$Q = \frac{k}{n}AR_h^{2/3}S^{1/2} \quad (3.4)$$

¹¹ $k=1$ if SI units and $k=1.486$ if English units

¹² R_h is equal to Cross sectional Area (A) divided by Wetted Perimeter (P)

For each stream a unique stage discharge curve was created to a stage that at least reached the extent of its bank. In many cases, detailed floodplain survey allowed for discharges to be calculated at depths well above the bankfull stage. A given Levellogger reading could then be associated with a flow rate, resulting in 10-minute flow values from July of 2009 through June of 2011 (and continuing). At each of the 6 USGS sites, long-term datasets were available allowing for 3-year-or-greater datasets to be downloaded at 15 minute or daily average resolution.

Bankfull discharge was estimated based upon the [estimated] bankfull elevation determined previously in the geomorphology section (Chapter 3.4.3).

3.6 DETERMINING REGIONAL CURVES

Using the data derived in sections 3.3, 3.4, and 3.5 regional curves were plotted for the Lower Pee Dee in the coastal plains of South Carolina as described in Dunne and Leopold (1978) and later modified in Leopold (1994). This method has since been used to predict stream geometry in the Pacific Northwest (Castro and Jackson, 2001), Maryland and Pennsylvania (Cinotto, 2003), Florida, Alabama, and Georgia (Metcalf, 2009), and the North Carolina piedmont region (Doll et al., 2002) and coastal plain (Doll et al., 2002; Sweet and Geratz, 2003). These plots included watershed area as the independent variable against dependent variables of bankfull flow rate, bankfull width, bankfull depth, and bankfull cross sectional area.

3.7 ANALYSIS OF BED MATERIAL

Bed material analysis at each site used averaged results of 5 samples across the nearest riffle, within the estimated bankfull. This occurred at a riffle just upstream or downstream of the Levellogger position, but well away (at least 3 bankfull widths) from any possible impoundment or obstruction to

flow. In some cases this was not possible due to the amounts of large woody debris present in the channel. Each sample was taken using a Shallow Water Bottom Dredge (AMS™, 2010) and placed into a labeled sample bag. Each bag was placed into a drying oven at set to 100°C for 24 hours to dry.

Samples were weighed and poured through a series of sieve screens [a No. 5 (4 mm), No. 10 (2 mm), and finally a pan] using a Ro-Tap® (W.S. Tyler™, 2009) for 2 minutes on each sample. The sediment that passed through both screens onto the pan was weighed and a small, representative portion was ran through a Beckman Coulter® LS 13 320 Laser Diffraction Particle Size Analyzer (Beckman Coulter™, Brea, CA) for further analysis. Sediment that remained on the No. 10 screen was weighed and recorded. Sediment that remained on the No. 5 screen was separated into 4-8 mm, 8-11.2 mm, 11.2-16 mm, 12-22.4 mm, 22.4-31.5 mm, 31.5-45 mm, 45-63 mm, and 63-75 mm groups, as assessed by their median dimensions. Each group was weighed and recorded. All data were normalized to percentage by weight and inputted into the publically available Gradistat Grain Size Analysis Program (Blott, 2000)¹³ for analysis and summary of the data. Outputs included a graph of the particle sizes as well as D_{10} , D_{50} , and D_{90} (the diameter of the 10th, 50th, and 90th percentile of grain sizes, respectively). Custom modifications to the program allowed for the outputs of D_{16} and D_{84} . Because each sample had been normalized to a percentage, the five samples were combined and again normalized to also be analyzed using the modified Gradistat program (Blott, 2000). In this way, the entire bed of each channel could have one, representative D_{16} , D_{50} , and D_{84} .

¹³ Gradistat can be downloaded at:
www.ceex.es/pipermail/rivers-list/attachments/20061004/.../gradistat.xls

3.8 COMPONENTS OF STREAM FLOW FUNCTION

Several methods were utilized in the determination of stream function, including the Qualitative Habitat Evaluation Index (Mecklenburg and Ward, 2009), the Richards-Baker Flashiness Index (Baker et al., 2004), Hammer Number (Pizzuto et al., 2000), the Temperature Variation Index (TVI), annual bankfull occurrence (Metcalf et al., 2009; Sweet and Geratz, 2003; etc.), and bed load divided by watershed area. Regional Curves (Metcalf et al., 2009; Cinotto, 2003; Sweet and Geratz, 2003; Doll et al., 2002; Castro and Jackson, 2001; Dunne and Leopold, 1978) and Copeland's stability curves (Copeland, 1994) were also investigated.

3.8.1 Qualitative Habitat Evaluation Index

Before any other assessment began on a stream site, the Qualitative Habitat Evaluation Index (QHEI) was determined (Rankin, 1989). This involved a visual survey of a given stream reach (surrounding the stage recorder and cross section) that assessed the stream habitat state. A field sheet was filled out and the total score was added up. The field sheet is shown in Figure 3.6. Developed for streams of Ohio, *Gradient*, the last portion of the stream score was omitted due to the use of Ohio stream morphology in the process of the defining the 10-point metric. Otherwise, all other protocol and can be found in Rankin (1989).

Qualitative Habitat Evaluation Index Field Sheet QHEI Score:

River Code: _____ RM: _____ Stream _____			
Date _____ Location _____			
Scorers Initials: _____ Comments _____			
1] SUBSTRATE (Check ONLY Two Substrate TYPE BOXES; Estimate % present);			
TYPE	POOL RIFFLE	POOL RIFFLE	SUBSTRATE ORIGIN
<input type="checkbox"/> BLDR/SLBS [10]	<input type="checkbox"/> GRAVEL [7]	<input type="checkbox"/> LIMESTONE [1]	<input type="checkbox"/> SILT:
<input type="checkbox"/> BOULDER [9]	<input type="checkbox"/> SAND [6]	<input type="checkbox"/> TILLS [1]	<input type="checkbox"/> -SILT HEAVY [-2]
<input type="checkbox"/> COBBLE [8]	<input type="checkbox"/> BEDROCK [5]	<input type="checkbox"/> WETLANDS [0]	<input type="checkbox"/> -SILT MODERATE [-1]
<input type="checkbox"/> HARDPAN [4]	<input type="checkbox"/> DETRITUS [3]	<input type="checkbox"/> HARDPAN [0]	<input type="checkbox"/> -SILT NORMAL [0]
<input type="checkbox"/> MUCK [2]	<input type="checkbox"/> ARTIFICIAL [0]	<input type="checkbox"/> SANDSTONE [0]	<input type="checkbox"/> -SILT FREE [1]
<input type="checkbox"/> SILT [2]		<input type="checkbox"/> RIP/RAP [0]	<input type="checkbox"/> -EXTENSIVE [-2]
		<input type="checkbox"/> LACUSTRINE [0]	<input type="checkbox"/> -MODERATE [-1]
		<input type="checkbox"/> SHALE [-1]	<input type="checkbox"/> -NORMAL [0]
		<input type="checkbox"/> COAL FINES [-2]	<input type="checkbox"/> -NONE [1]
NOTE: (Ignore sludge originating from point-sources; score on natural substrates)			
NUMBER OF SUBSTRATE TYPES: <input type="checkbox"/> 5 or More [2]		EMBEDDED NESS:	
<input type="checkbox"/> 4 or Less [0]			
COMMENTS: _____			
2] INSTREAM COVER (see back for instructions for additional cover scoring method)			
TYPE: (Check All That Apply)		AMOUNT: (Check ONLY One or check 2 and AVERAGE)	
<input type="checkbox"/> UNDERCUT BANKS [1]	<input type="checkbox"/> POOLS > 70 cm [2]	<input type="checkbox"/> OXBOWS, BACKWATERS [1]	<input type="checkbox"/> - EXTENSIVE > 75% [11]
<input type="checkbox"/> OVERHANGING VEGETATION [1]	<input type="checkbox"/> ROOTWADS [1]	<input type="checkbox"/> AQUATIC MACROPHYTES [1]	<input type="checkbox"/> - MODERATE 25-75% [7]
<input type="checkbox"/> SHALLOWS (IN SLOW WATER) [1]	<input type="checkbox"/> BOULDERS [1]	<input type="checkbox"/> LOGS OR WOODY DEBRIS [1]	<input type="checkbox"/> - SPARSE 5-25% [3]
<input type="checkbox"/> ROOTMATS [1]	COMMENTS: _____		<input type="checkbox"/> - NEARLY ABSENT < 5% [1]
3] CHANNEL MORPHOLOGY: (Check ONLY One PER Category OR check 2 and AVERAGE)			
SINUOSITY	DEVELOPMENT	CHANNELIZATION	STABILITY
<input type="checkbox"/> -HIGH [4]	<input type="checkbox"/> -EXCELLENT [7]	<input type="checkbox"/> -NONE [6]	<input type="checkbox"/> -HIGH [3]
<input type="checkbox"/> -MODERATE [3]	<input type="checkbox"/> -GOOD [5]	<input type="checkbox"/> -RECOVERED [4]	<input type="checkbox"/> -MODERATE [2]
<input type="checkbox"/> -LOW [2]	<input type="checkbox"/> -FAIR [3]	<input type="checkbox"/> -RECOVERING [3]	<input type="checkbox"/> -LOW [1]
<input type="checkbox"/> -NONE [1]	<input type="checkbox"/> -POOR [1]	<input type="checkbox"/> -RECENT OR NO RECOVERY [1]	
		MODIFICATIONS/OTHER	<input type="checkbox"/> -SNAGGING
		<input type="checkbox"/> -RELOCATION	<input type="checkbox"/> -IMPOUND.
		<input type="checkbox"/> -CANOPY REMOVAL	<input type="checkbox"/> -ISLANDS
		<input type="checkbox"/> -DREDGING	<input type="checkbox"/> -LEVEED
		<input type="checkbox"/> -ONE SIDE CHANNEL MODIFICATIONS	<input type="checkbox"/> -BANK SHAPING
COMMENTS: _____			
4] RIPARIAN ZONE AND BANK EROSION (check ONE box per bank or check 2 and AVERAGE per bank) ★ River Right Looking Downstream★			
RIPARIAN WIDTH		FLOOD PLAIN QUALITY (PAST 100 Meter RIPARIAN)	
L R (Per Bank)	L R (Most Predominant Per Bank)	L R	BANK EROSION
<input type="checkbox"/> -WIDE > 50m [4]	<input type="checkbox"/> -FOREST, SWAMP [3]	<input type="checkbox"/> -CONSERVATION TILLAGE [1]	<input type="checkbox"/> -NONE/LITTLE [3]
<input type="checkbox"/> -MODERATE 10-50m [3]	<input type="checkbox"/> -SHRUB OR OLD FIELD [2]	<input type="checkbox"/> -URBAN OR INDUSTRIAL [0]	<input type="checkbox"/> -MODERATE [2]
<input type="checkbox"/> -NARROW 5-10m [2]	<input type="checkbox"/> -RESIDENTIAL, PARK, NEW FIELD [1]	<input type="checkbox"/> -OPEN PASTURE, ROWCROP [0]	<input type="checkbox"/> -HEAVY/SEVERE [1]
<input type="checkbox"/> -VERY NARROW < 5m [1]	<input type="checkbox"/> -FENCED PASTURE [1]	<input type="checkbox"/> -MINING/CONSTRUCTION [0]	
<input type="checkbox"/> -NONE [0]			
COMMENTS: _____			
5] POOL/GLIDE AND RIFFLE/RUN QUALITY			
MAX. DEPTH	MORPHOLOGY	CURRENT VELOCITY (POOLS & RIFFLES!)	Pool/Current
(Check 1 ONLY!)	(Check 1 or 2 & AVERAGE)	(Check All That Apply)	
<input type="checkbox"/> - > 1m [6]	<input type="checkbox"/> - POOL WIDTH > RIFFLE WIDTH [2]	<input type="checkbox"/> - EDDIES [1]	<input type="checkbox"/> - TORRENTIAL [-1]
<input type="checkbox"/> - 0.7-1m [4]	<input type="checkbox"/> - POOL WIDTH = RIFFLE WIDTH [1]	<input type="checkbox"/> - FAST [1]	<input type="checkbox"/> - INTERSTITIAL [-1]
<input type="checkbox"/> - 0.4-0.7m [2]	<input type="checkbox"/> - POOL WIDTH < RIFFLE W. [0]	<input type="checkbox"/> - MODERATE [1]	<input type="checkbox"/> - INTERMITTENT [-2]
<input type="checkbox"/> - 0.2-0.4m [1]		<input type="checkbox"/> - SLOW [1]	
<input type="checkbox"/> - < 0.2m [POOL=0]	COMMENTS: _____		
CHECK ONE OR CHECK 2 AND AVERAGE			
RIFFLE DEPTH	RUN DEPTH	RIFFLE/RUN SUBSTRATE	RIFFLE/RUN EMBEDDEDNESS
<input type="checkbox"/> - Best Areas > 10 cm [2]	<input type="checkbox"/> - MAX > 50 [2]	<input type="checkbox"/> - STABLE (e.g., Cobble, Boulder) [2]	<input type="checkbox"/> - NONE [2]
<input type="checkbox"/> - Best Areas 5-10 cm [1]	<input type="checkbox"/> - MAX < 50 [1]	<input type="checkbox"/> - MOD. STABLE (e.g., Large Gravel) [1]	<input type="checkbox"/> - LOW [1]
<input type="checkbox"/> - Best Areas < 5 cm [RIFFLE=0]		<input type="checkbox"/> - UNSTABLE (Fine Gravel, Sand) [0]	<input type="checkbox"/> - MODERATE [0]
			<input type="checkbox"/> - EXTENSIVE [-1]
COMMENTS: _____		<input type="checkbox"/> - NO RIFFLE [Metric=0]	
6] GRADIENT (ft/mi): _____ DRAINAGE AREA (sq.mi.): _____			
		%POOL: 	%GLIDE:
		%RIFFLE: 	%RUN:

* Best areas must be large enough to support a population of riffle-obligate fish species.

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Figure 3.6 – QHEI field survey sheet. This form was completed at each site before other site assessment began.

3.8.2 Richards-Baker Flashiness

For the Richards-Baker Flashiness Index, previously-calculated flow values were grouped on a per day basis and averaged into a mean daily flow rate for the calculation of the Richards-Baker Flashiness Index (Baker et al., 2004). At each of the 6 USGS sites, long-term datasets were available allowing for 3-year-or-greater datasets to be analyzed for the Richards-Baker Flashiness Index, whose equation is shown below. In this equation, q_i is the mean daily flow rate on a given day, q_{i-1} is the mean daily flow rate from the day before, and n is one less than the total number of days in the sample (because the difference between a given day and its previous day can only be calculated on the second day).

$$\text{Richards} - \text{Baker Flashiness Index} = \frac{\sum_{i=1}^n |q_i - q_{i-1}|}{\sum_{i=1}^n q_i} \quad (3.5)$$

Upon analyzing the equation, the minimum flashiness value is 0 and could only occur if the average daily flow rate was a constant value. Theoretically, RBI does not have a maximum bound, although Baker (2004) found the maximum RBI of 1.3 in a study of 515 streams throughout the Midwest. However, this value could be even larger in mountainous regions, agricultural ditches, or other settings.

3.8.3 Temperature Variation

Stream temperature was taken with the same instrument as water level, the Solinst Levellogger Gold® (Solinst™, Ontario). Stream temperature was simplified to daily and monthly averages resulting in a chart for each site much like Figure 3.7.

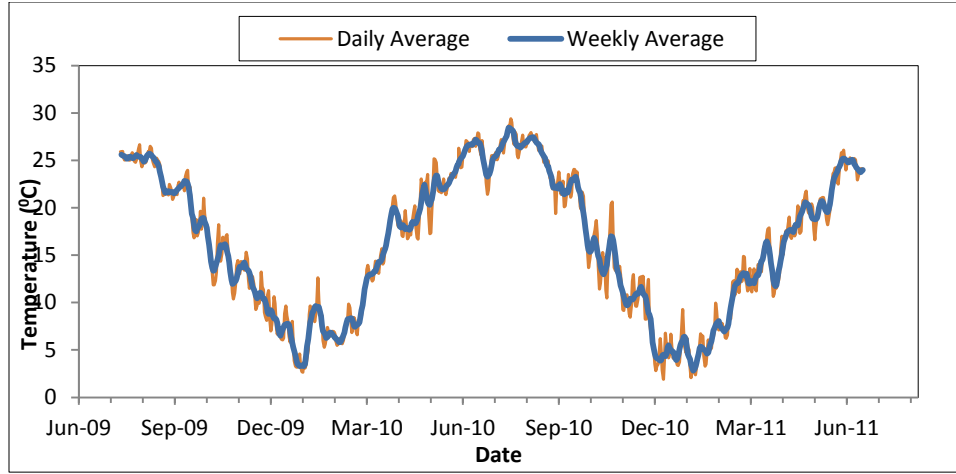


Figure 3.7 – Temperature profile of Huckleberry Branch over 2-year period of record. The orange line shows the daily averages and the thicker blue line illustrates the 7-day floating average used to calculate temperature variation.

A temperature variation index (TVI) was developed for this study and applied to the average daily temperatures measured at non-USGS study sites. The index is a measure of the average variation of daily average temperatures from a 7-day floating average of daily temperatures over the period of record and was used as an attempt to offset the effect of diurnal variation of temperature. The difference between the 7-day floating index from a particular day and the day before were averaged over the period of record. This temperature variation index (TVI) is summarized in Equation 3.6. In this equation, T_i is the mean daily temperature (°C or °F) on a given day T_{i-1} is the mean daily temperature (°C or °F) from the day before, etc.), N is the total number of measurements and TVI is the temperature variation index.

$$TVI = \frac{\sum_{i=4}^{N-3} \left| T_i - \frac{(T_{i-3} + T_{i-2} + T_{i-1} + T_i + T_{i+1} + T_{i+2} + T_{i+3})}{7} \right|}{N - 6} \quad (3.6)$$

The reason for subtracting 6 from the total number of measurements is due to the use of the floating 7-day average (you lose 3 values at each end of the data).

3.8.4 Hammer Number

The Hammer Number (H) is defined as a channel property (Pizzuto et al., 2000) and provides insight into the stability of a stream. This number is simply a measure of the amount of water that is discharged per unit of watershed area and defined in Equation 3.7. In Equation 3.7, H is the Hammer number (cfs/sq. mi), Q_{bkf} is the bankfull flow rate (cfs), and D_A is the drainage area of the watershed.

$$H = \frac{Q_{bkf}}{D_A} \quad (3.7)$$

Although utilized originally under the context of developed watershed areas (Pizzuto et al., 2000), stark contrasts in this number in a relatively undeveloped landscape have helped to identify other causes of stream instability.

3.8.5 Bankfull Recurrence

Although the term *bankfull recurrence* is often in literature (Sweet and Geratz, 2003; Metcalf et al. 2009; etc.) the dataset from this preliminary analysis of stream function was only 2 years and was therefore not deemed a long enough period of record to assume *recurrence*. Instead, *bankfull occurrence* was used to illustrate the average annual number of flow events that exceed bankfull depth. For the purpose of this study, an *event* was defined as a series of daily average flow rates that all exceeded the defined bankfull flow rate. A single event could last 10 or more days if the flow rate was maintained above the bankfull bench. However, if the flow rate dropped below the bench and then rose back above it, this was considered a second event.

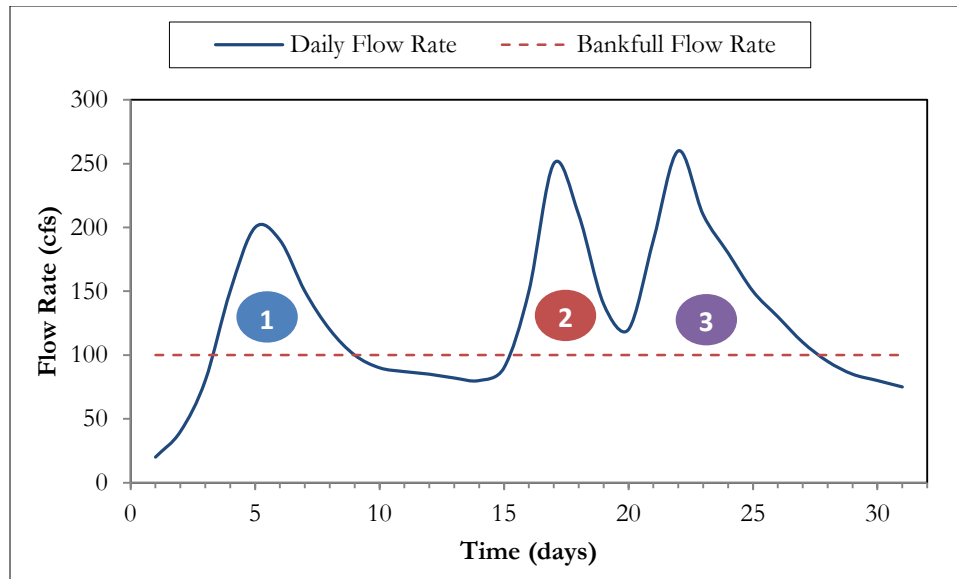


Figure 3.8 – Hypothetical stream hydrograph over one-month period. Note that hydrograph peaks are labeled 1, 2, and 3.

An example of this concept is illustrated in Figure 3.8, where the hydrograph peak 1 would represent its own bankfull occurrence; while hydrograph peaks 2 and 3 would be counted as a single bankfull occurrence because the flow rate never dropped below the bankfull benchmark.

3.8.6 Bed Load Flux

Bed load flux was calculated using Brownlie's (1981) resistance equations for sand-bed streams (USDA-NRCS, 2006). Regime (upper or lower) was first determined using equations 3.8 and 3.9. In these equations, V is velocity, Where R_b is the hydraulic radius associated with the bed S is slope (ft/ft), D_{50} is the median grain size (ft), D_{84} is the grain size at the 84th percentile, D_{16} is the grain size at the 16th percentile, σ is the gradation coefficient, C is the sediment concentration (ppm) over the bed, γ_s is the specific weight of the sediment (lb/ft³), γ is the specific weight of water (lb/ft³), ν is the kinematic viscosity of water (ft²/s), S is slope (ft/ft), V is velocity (fps), d is average water depth (ft), and g is acceleration of gravity (ft/s²).

$$F_g = \frac{V}{\sqrt{gD_{50}[\frac{\gamma-\gamma_s}{\gamma}]}} \quad (3.8)$$

$$F_g' = \frac{1.74}{S^{0.3333}} \quad (3.9)$$

If the slope (S) was greater than 0.006 or F_g was great than $1.25F_g'$, then the stream was classified as being in an upper regime. If F_g was less than $0.8F_g'$, then the stream was classified as lower regime. The transitional area of $0.45F_g'$ difference is known as being a transitional regime. In this study, these streams were classified as transition streams, and therefore both upper and lower regime paths were taken. When streams where classified as an upper regime, Equation 3.10a was used. When streams were classified as a lower regime, Equation 3.10b was used.

$$R_b = 0.2836D_{50}q_*^{0.6539}S^{-0.2542}\sigma^{0.0813} \quad (3.10a)$$

$$R_b = 0.3742D_{50}q_*^{0.6539}S^{-0.2542}\sigma^{0.1050} \quad (3.10b)$$

$$q_* = \frac{Vd}{\sqrt{gD_{50}^3}} \quad (3.11)$$

$$\sigma = 0.5\left(\frac{D_{84}}{D_{50}} + \frac{D_{50}}{D_{16}}\right) \quad (3.12)$$

Concentration (ppm) was then calculated using Equation 3.13, which is derived from the same data that Brownlie (1981) derived his own sediment resistance equations (Copeland, 1994).

$$C = 9022(F_g - F_{go})^{1.978}S^{0.6601}\left(\frac{R_b}{D_{50}}\right)^{-0.3301} \quad (3.13)$$

$$F_{go} = \frac{4.596\tau_{*0}^{0.5293}}{S^{0.1405}\sigma^{0.1606}} \quad (3.14)$$

$$\tau_{*0} = 0.22Y + 0.06 * 10^{-7.7Y} \quad (3.15)$$

$$Y = \left(\sqrt{\frac{\gamma_s - \gamma}{\gamma}} \right)^{-0.6} \quad (3.16)$$

$$R_g = \frac{\sqrt{gD_{50}^3}}{v} \quad (3.17)$$

From concentration, sediment discharge and average concentration could be calculated using equations 3.18 and 3.19. In these equations, Q_s is sediment transport (lb/s), B is the projected base width of the stream, and Q is flow rate (ft³/s).

$$Q_s = \gamma CBDV \quad (3.18)$$

$$\bar{C} = \frac{Q_s}{Q} \quad (3.19)$$

In this study, the projected base length (B) was the top width of the channel at an estimated base flow, as evident by both frequent field observation and indicators in the cross section of the stream. This was due to significant deviations in the cross-sections from the traditional trapezoidal cross section as well as significant variations between streams. By estimating the base flow top width as the active bed, this helped to normalize the method of determining the base-width (B) across many different channel shapes.

Bed load flux was then converted into units of tons/yr and divided by watershed area as to nominalize the effect of stream size and rather, investigate bed load on a per-square-mile basis. The resulting units for annual bed load divided by watershed area (BL/A_w*yr) resulted in (tons sediment/yr*mi²).

3.9 STATISTICAL ANALYSES

Statistical analysis was primarily a function of comparing different groups of collected data in order to address the following four null hypotheses.

H_{0a}: Measures of land cover do not influence components of stream flow function.

H_{0b}: Land cover indices do not affect stream flow indices, and are therefore not spatially limited.

H_{0c}: Hydraulic geometry is independent of catchment area within the Pee Dee watershed of South Carolina.

H_{0d}: Characteristic bed material is not influenced by any individual measure of stream flow function, stream geomorphology, or land use.

These groupings included components of stream flow function (QHEI, RBI, H, Bankfull Occurrence, TVI, and $BL/A_w \cdot \text{yr}$), measures of land cover (which included all scales of percentages of agriculture, forest, wetland, and imperviousness, as well as LDI and CN), stream geomorphology (slope, catchment area, and Manning's n , as well as bankfull measures of width, depth, cross sectional area, and flow rate), and characteristic bed material (D_{16} , D_{50} , D_{84}).

3.9.1 Normalizing the Data

Parametric statistics require normal datasets for accurate analyses. All datasets were tested for normality using the Anderson-Darling Normality test. Non-normal data were normalized using log and square root transforms (taking the \log_{10} or square root of the entire dataset, respectfully). In the event that neither transform normalized the dataset, other transforms were attempted. The transforms used in this study are outlined in McCune and Grace (2002). Datasets that remained non-normal after all transforms were excluded from further analysis.

3.9.2 Correlation and Regression Analyses

Correlation analyses were ran between respective groups of datasets in order to address each of the null hypotheses. This included comparisons of components of stream flow function and land cover (H_{0a} and H_{0b}), watershed area and the remainder of stream geomorphology (H_{0c}), and characteristic bed substrate and all other groups (H_{0d}).

Correlations and respective probabilities for significance were calculated. In this study, significant correlations ($p < 0.05$) above a threshold correlation value was chosen similar to methods adopted by Jones et al. (2001). The threshold correlation chosen for the study was $R = 0.6$. A second correlation threshold of $R = 0.7$ above which linear regression analyses were performed. Although no further analyses were performed on those cases between $R = 0.6$ and 0.7 , these correlations are discussed.

4 RESULTS

Sixteen sites were selected to be monitored within the upper Pee Dee watershed within the coastal plains of northern South Carolina. Drainage areas of the 16 sites ranged from 7 to 664 square miles and covering five EPA Level IV ecoregions (Olsen et al., 2001). These included the Atlantic Southern Loam Plains, Sand Hills, Southern Outer Piedmont, Carolina Slate Belt, and Triassic Basins. All sampling sites fell into the ecoregions of the Sand Hills (10 sites) or the Atlantic Southern Loam Plains (6 sites) (Figure 4.2). Stream densities in all the study watersheds had an average stream density of 0.36 miles of stream per square mile and ranged between 0.21 and 0.59 miles of stream length per square mile of watershed area (A_c). The highest stream density (0.59 mi/mi²) occurred in the Jeffries Creek (DNR) watershed and the lowest stream density (0.21 mi/mi²) occurred in the Hams Creek (DNR) watershed. Because stream length and watershed area produced such a linear trend (Figure 4.1), watershed area could be used in place of stream length within a watershed. Site visits and initial evaluations resulted in a range of QHEI scores from 34.5 (at Jeffries Creek USGS) to 78 (at Hams Creek DNR). Average QHEI score for all the sites was 56. A summary of watershed areas, habitat condition (QHEI) and ecoregions is presented in Table 4.1 and illustrated in Figure 4.2. Notice that some of the site names are duplicates. To distinguish duplicate sites, refer to its association (i.e. DNR, USGS)¹⁴ or associated site code.

¹⁴ Whenever an individual site is referenced, it will be done so as in Table 4.1 where the name will be referenced first and then, if necessary, its association will be in parenthesis.

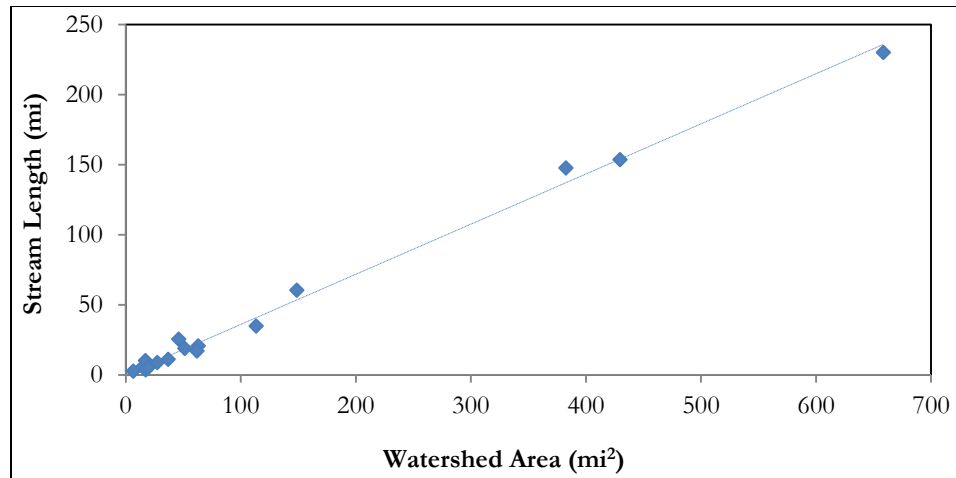


Figure 4.1 – Scatter plot showing the variation of stream length with watershed area for all sample sites in the lower Pee Dee.

Table 4.1 – Summary of watershed areas and ecoregions. Level IV ecoregions in this chart include Southern Outer Piedmont (SoOP), Carolina Slate Belt (CSB), Triassic Basins (TrB), Atlantic Southern Loam Plains (ASLP) and Sand Hills (SH) with the bold font representing the Ecoregion at the sampling site.

Site Name (Association)	Site Code	A _w (mi ²)	QHEI	Stream Density (mi/mi ²)	Level IV Ecoregion [Ecoregion (%)]*
Huckleberry Branch	HCKLBRY	6.7	67.5	1.68	SH (100)
Little Fork Creek*	FRKUSGS	15.2	65.0	1.74	SH (85), CSB(15)
Jefferies Creek ⁺	JEFFDNR	17.3	48.0	2.604	ASLP (100)
Hams Creek ⁺	HAMSCRK	17.6	78.0	0.95	SH (100)
Juniper Creek	JNPRMAF	19.7	43.0	1.19	SH (100)
Crooked Creek ⁺	CRKDDNR	27.9	57.5	0.61	SH(80), ASLP (20)
Juniper Creek ⁺	JNPRDNR	37.2	61.5	1.33	SH (100)
Jefferies Creek*	JEFUSGS	46.8	34.5	2.41	ASLP (100)
Black Creek below Chesterfield*	BLKCHES	51.8	63.5	1.62	SH (100)
Little Lynches River ⁺	LILYNCH	59.7	48.0	1.70	SH (75), CSB(25)
Crooked Creek	CRKDMAF	64.6	66.5	3.39	ASLP (62), SH(38)
Black Creek near McBee*	BLCKMAC	114.1	55.0	1.36	SH (100)
Thompson Creek	THOMPSN	148.7	55.5	1.78	CSB(57), SH (27), TrB(16)
Lynches River at Hwy 1	LYNHWY1	385.4	50.0	1.70	SH (57), CSB(41), TrB(2)
Black Creek near Quinby*	BLKQUIN	439.0	57.5	1.59	SH(51), ASLP (49)
Lynches River near Bishopville*	LYNBISH	663.3	43.5	1.54	CSB(62), SH(13), ASLP (12), SoOP(11), TrB(2)

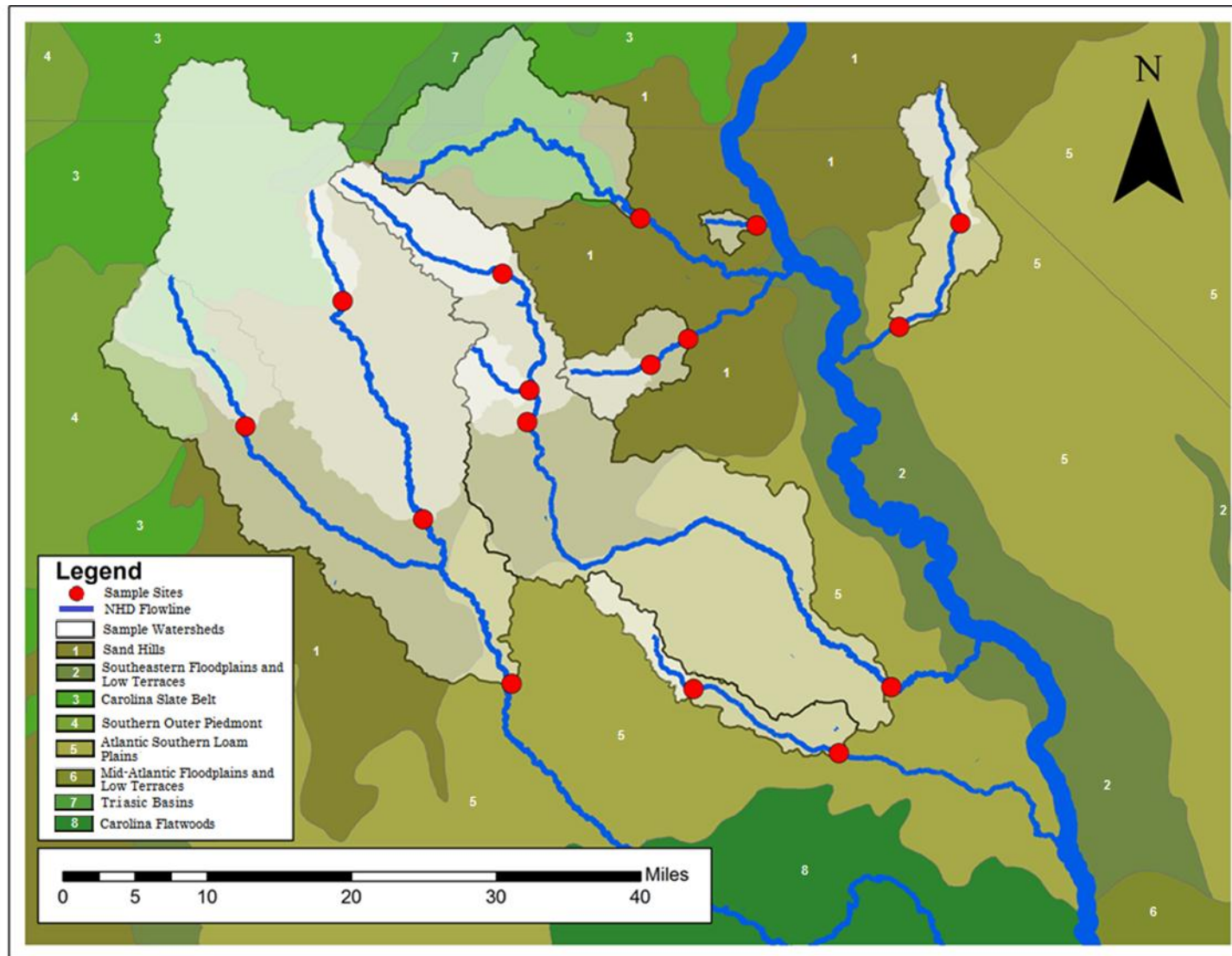


Figure 4.2 – Sampling sites, drainage area and ecoregions within the Lower Pee Dee watershed, SC.

4.1 LANDSCAPE ANALYSES

Results of the landscape analyses tended to differ drastically within the same watershed when analyzed at different scales. Recall that the scales of analyses included *catchment* scale and 4 riparian buffer scales (*200 m*, *1000 m*, *2000 m*, and the *entire riparian buffer*). The most extreme example occurred at Huckleberry Branch, where the total impervious area varied from 0.07 to 4.17% across the 5 scales of analyses. The least variation between scales of analyses occurred at Hams Creek, where LDI ranged only from 0.01 to 0.03 between the various scales of analyses.

LDI scores ranged from 0 to 0.19 (maximum possible is 0.9) with the lowest values typically occurring within one of the various riparian buffer scales (*200 m*, *1000 m*, *2000 m*, or the *entire riparian buffer*) and the highest values occurring when analyzed at the *catchment* scale. The only exception was Jefferies Creek (USGS), where the maximum LDI values fell in the 200 m riparian buffer and entire catchment scales.

Percent agriculture includes all row-crop agriculture under the 2006 NLCD land classification system. Percent forested includes pine, deciduous and mixed forest classes. Percent wetland included all 2006 NLCD land classified as herbaceous wetland and emergent herbaceous wetland classes outlined in the 2006 NLCD land cover map. Within the *catchment* scale, agricultural land ranged from 5.2% to 50% land cover, forested land ranged from 16.5% to 63.6% land cover, wetlands ranged from 3.5% to 20.8% land cover, and impervious area ranged from 0.42% to 4.17%. This differed significantly from the various buffer scales, where agricultural, forested, developed, and impervious land classes and maxima reached 57.9%, 100%, 45.2%, and 9.02% land cover, respectively. Minima for the land cover classes of forest and agricultural in the various buffer scales were 0%. However, wetlands within the buffered region of the watershed ranged between 5% and 100% with most sites (>65%) having greater than 50% coverage within the *200 m*, *1000 m*, and *2000 m buffer* scale classes.

Average curve numbers ranged from 36.6 to 75.0 within the *catchment* scale and 25.7 to 75.8 within the various riparian buffer scales. Watersheds with lower curve numbers tended to be dominated by more natural (typically forested) land cover. Those with higher numbers tended to have more agricultural and developed landscapes. For example, the highest CN of any of the watershed scales discussed occurred at Jeffries Creek (DNR), and was 75.8 at the *entire riparian buffer* scale. Agricultural land cover dominated this scale with the second largest recorded in the study at 52.8%. Huckleberry Branch was similar at the *entire riparian buffer* scale, with agricultural land cover comprising 37% of the landscape under consideration, and a CN of 71. The presence of developed surfaces (measured by impervious area) also played a role in increasing the average CN of the watersheds. A good example is at Jeffries Creek (USGS), which had the highest impervious area at 5.92% at the *catchment* scale, and a corresponding average CN of 71. However, agricultural land cover at Jeffries Creek (USGS) cannot be neglected, contributing more than 15% coverage of the *catchment* scale. The variation in CN at the study sites appears to correspond to the presence of agricultural and developed land cover classes within the catchment. This is confirmed by plotting the sum of agricultural and developed land classes in the *entire riparian buffer* scale against CN. The resulting linear trend line had a significant coefficient of determination ($R^2=0.71$, $p< 0.001$) (Figure 4.3).

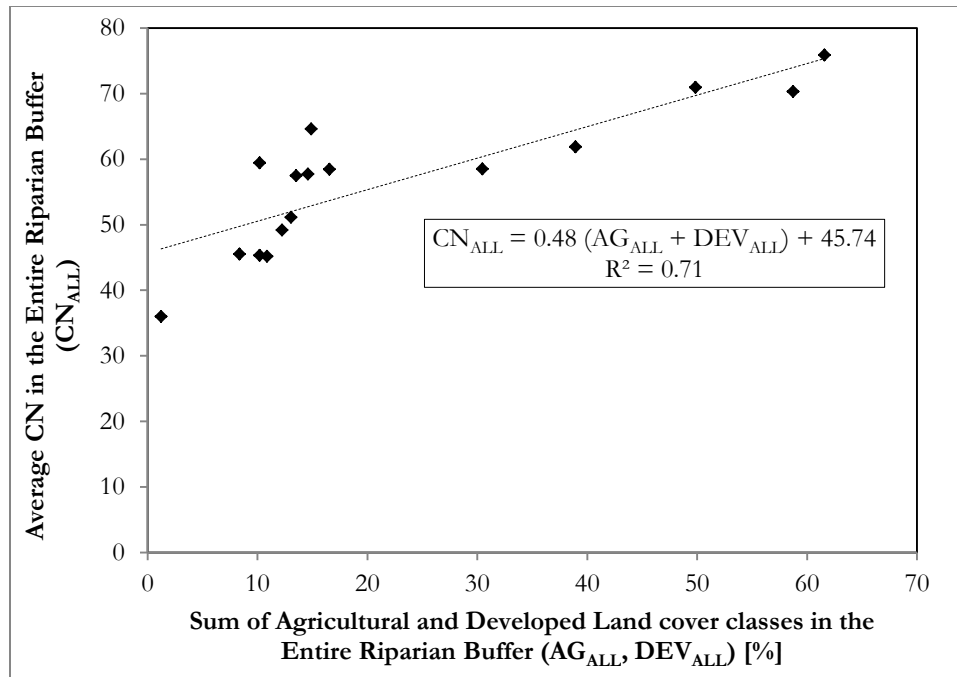


Figure 4.3 – Influence of agricultural and developed landscape in the entire riparian buffer on the average CN.

Figure 4.4a-h summarize data synthesized from the land cover analysis, including the specific land cover classes of agriculture, and forest, and wetland, as well as the Land Disturbance Index, total impervious area, and average Curve Number at each of the 5 scales of analyses (*200 m*, *1000 m*, *2000 m*, *entire riparian buffer*, and *catchment*). In Figure 4.3a, it is apparent that the catchment scale consistently has the highest LDI, suggesting that most intense urbanization occurs outside of the riparian buffer. The same trend is apparent in the case of TIA in Figure 4.3b, with most other scales yielding near-zero values. However, the catchment scale did not consistently yield the highest value for CN in a given watershed (Figure 4.4c). Neither did any scale dominate the minimum CN values. This is due to the fact that high curve numbers can be a result of both urban and natural landscapes, while TIA and LDI remain heavily influenced by urbanization. Figures 4.4d-h compare the percentages of land cover at the various land analysis scales. Figure 4.4d illustrates dominance of forested land at the catchment scale, with a less prominent influence at the entire riparian buffer scale

(Figure 4.4e). The dominance of wetlands within the three smallest riparian buffer scales (200 m, 1000 m, and 2000 m) is also apparent in Figures 4.4f-h.

Figures 4.5a-d illustrate the various landscape and land cover classes measurements within each respective watershed at the *catchment* scale, which are also summarized in the preceding figures (4.3a-f). However, these help illustrate spatial trends in the dataset. In Figure 4.5a, the watersheds summarized by high CNs (which are darker), tended be toward the outer edges. This was due to the Sandhills State Forest (approximately 75 square miles of forest) and surrounding area, which is primarily comprised of forested land cover, in the center of the sampling region of the sampling region. All outside edges of the sampling region tend to be characterized by larger proportions of agriculture or urban landscapes. In Figure 4.5b and Figure 4.5c, the highest LDI and TIA tend to be located in the eastern third of the maps. This could be due the placement of cities within the sampling region. Florence, Cheraw, and Hartsville, the three largest cities in the sampling region, are also located in the eastern third of the map. In Figure 4.5d, perhaps the most discernible trend is the larger influence of forested land cover on the center of the map and the greater influence of agriculture in the NW region evident by the two larger, highly agriculturally influenced watersheds that exist in the area. In each of the figures, overlapping watersheds are shown with the smallest watershed on top with each subsequent large water shed being shown with an additional border around its smaller counterpart. Distinct watersheds (not overlapping) are shown with a wider, dark boundary. Therefore, the largest watershed of any set of overlapping watersheds will be shown with the widest and darkest border of all those within it.

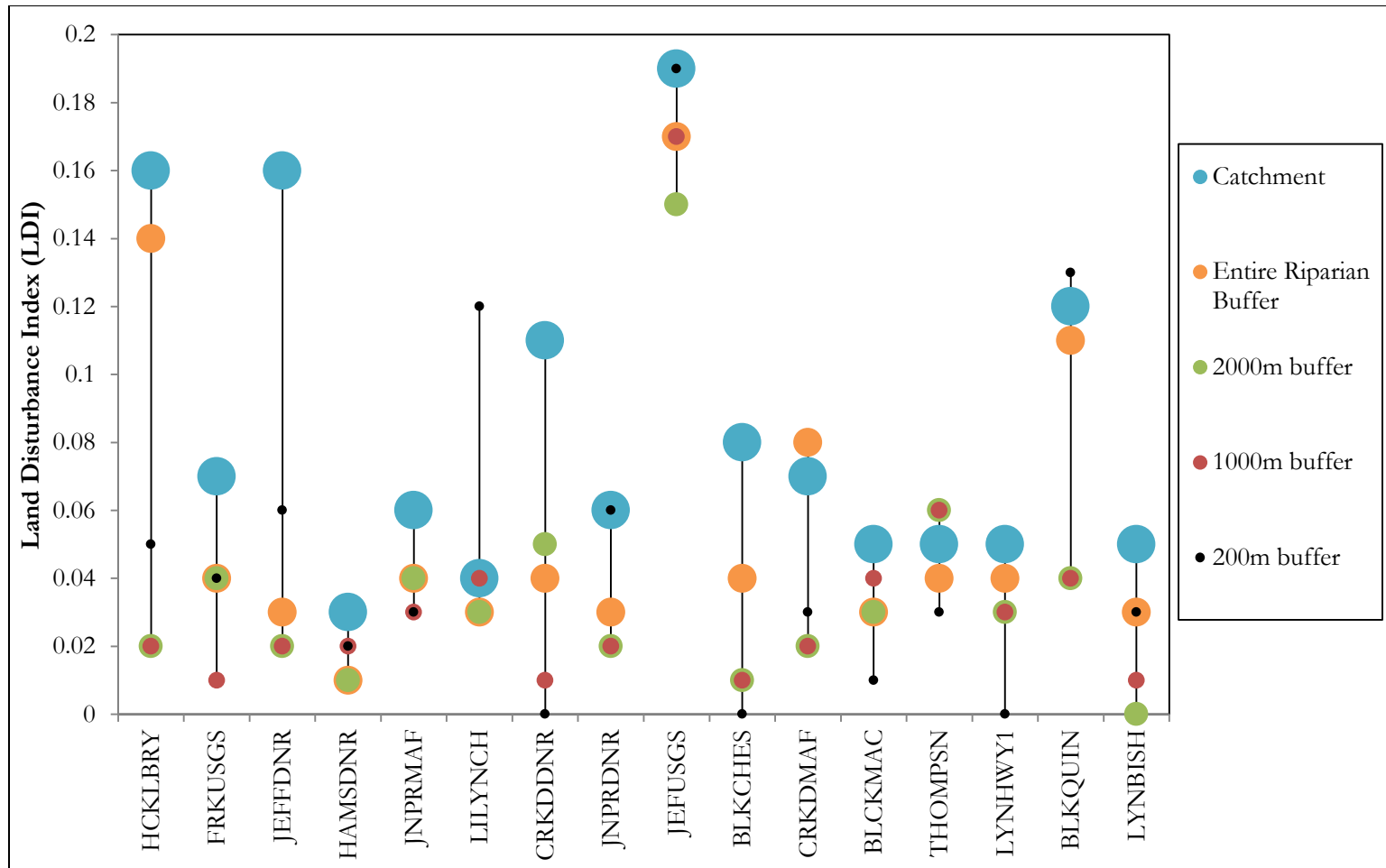


Figure 4.4a – Land Disturbance Indices (LDI) of the various watersheds at the 5 scales of landscape analyses (200 m, 1000 m, 2000 m, and entire riparian buffer and catchment scales). The size of the each data point represents the scale size.

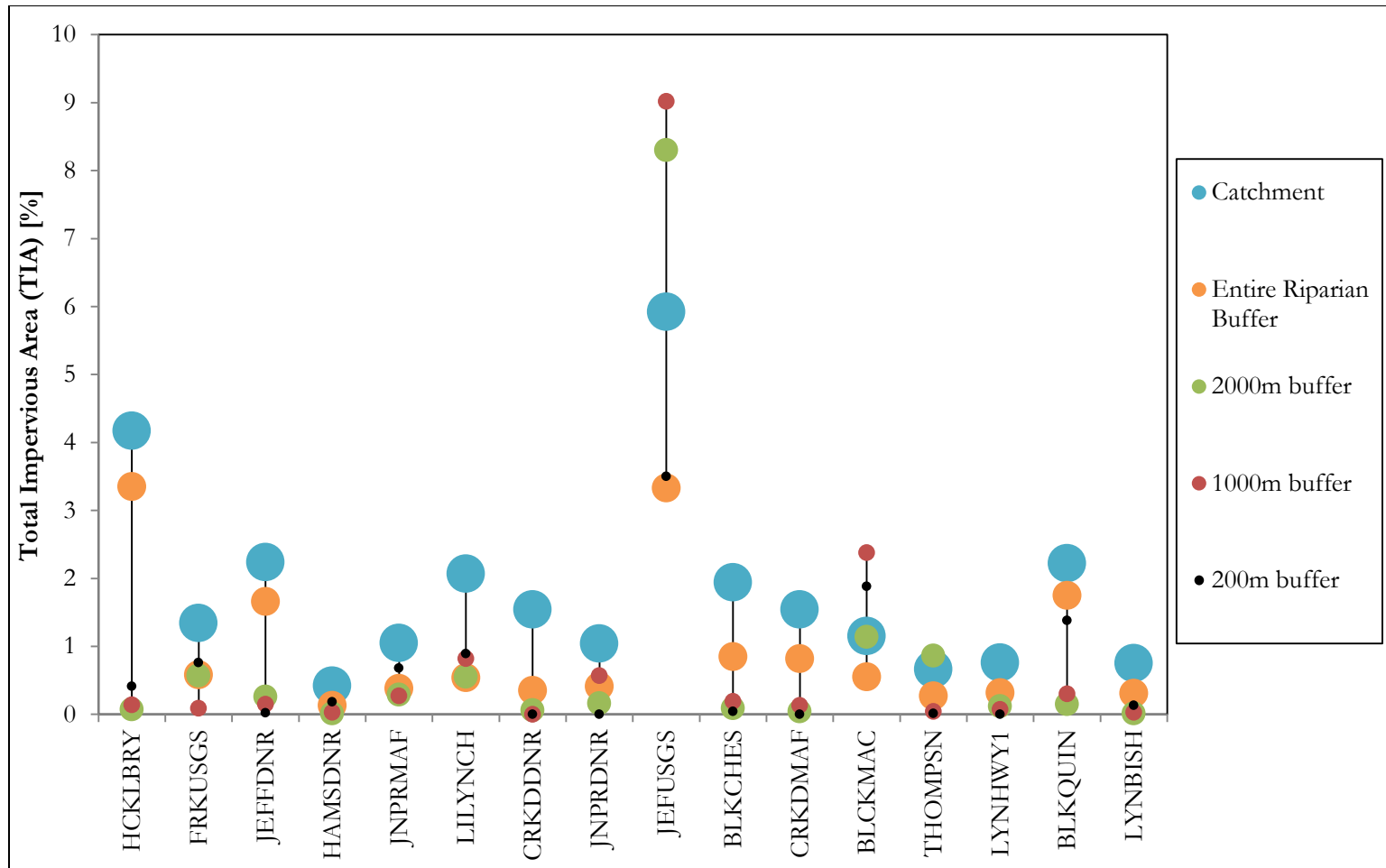


Figure 4.4b – Total Impervious Area (TIA) of the various watersheds at the 5 scales of landscape analyses (200 m, 1000 m, 2000 m, and entire riparian buffer and catchment scales). The size of the each data point represents the scale size.

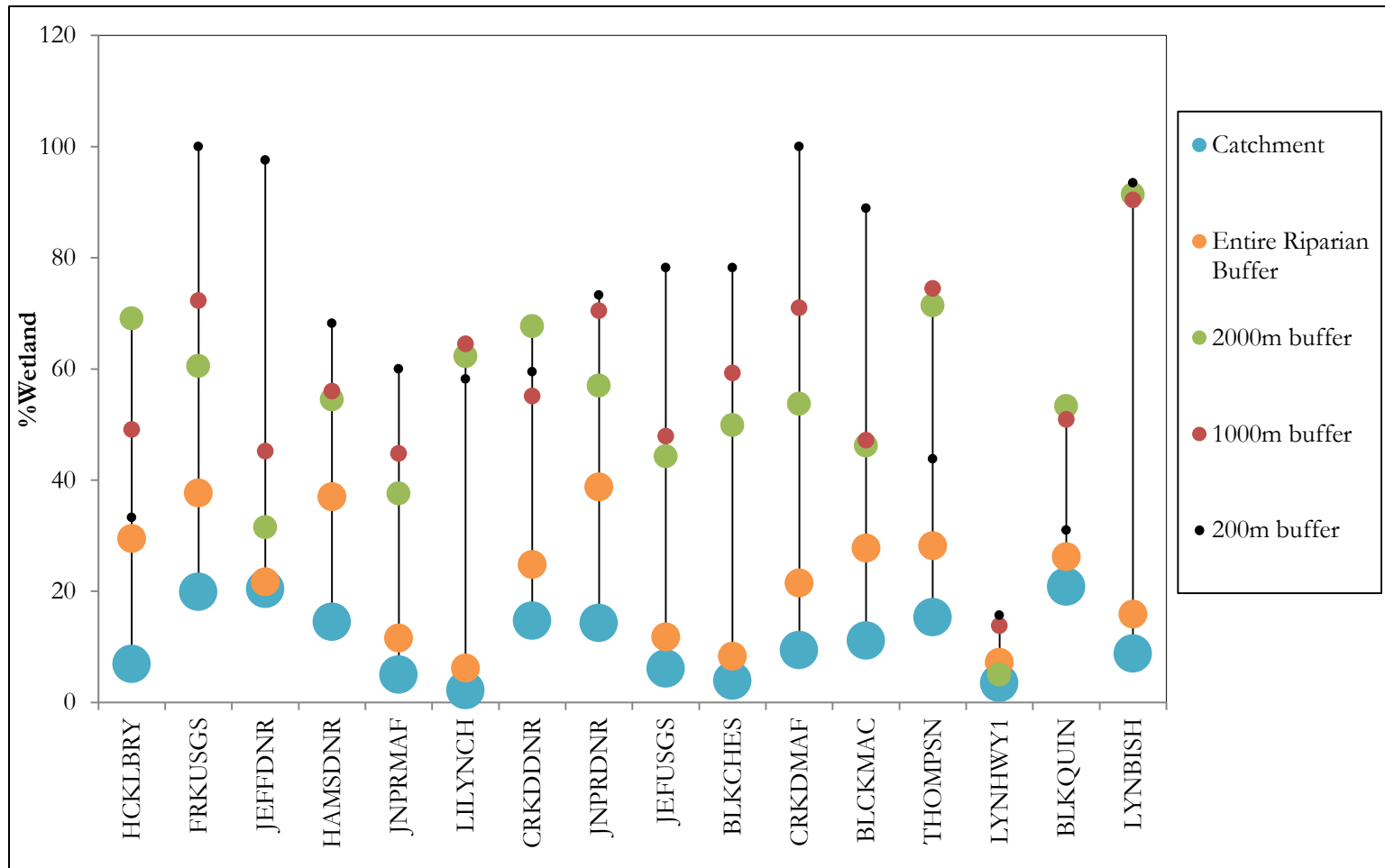


Figure 4.4c – Curve Numbers (CN) of the various watersheds at the 5 scales of landscape analyses (200 m, 1000 m, 2000 m, and entire riparian buffer and catchment scales). The size of the each data point represents the scale size.

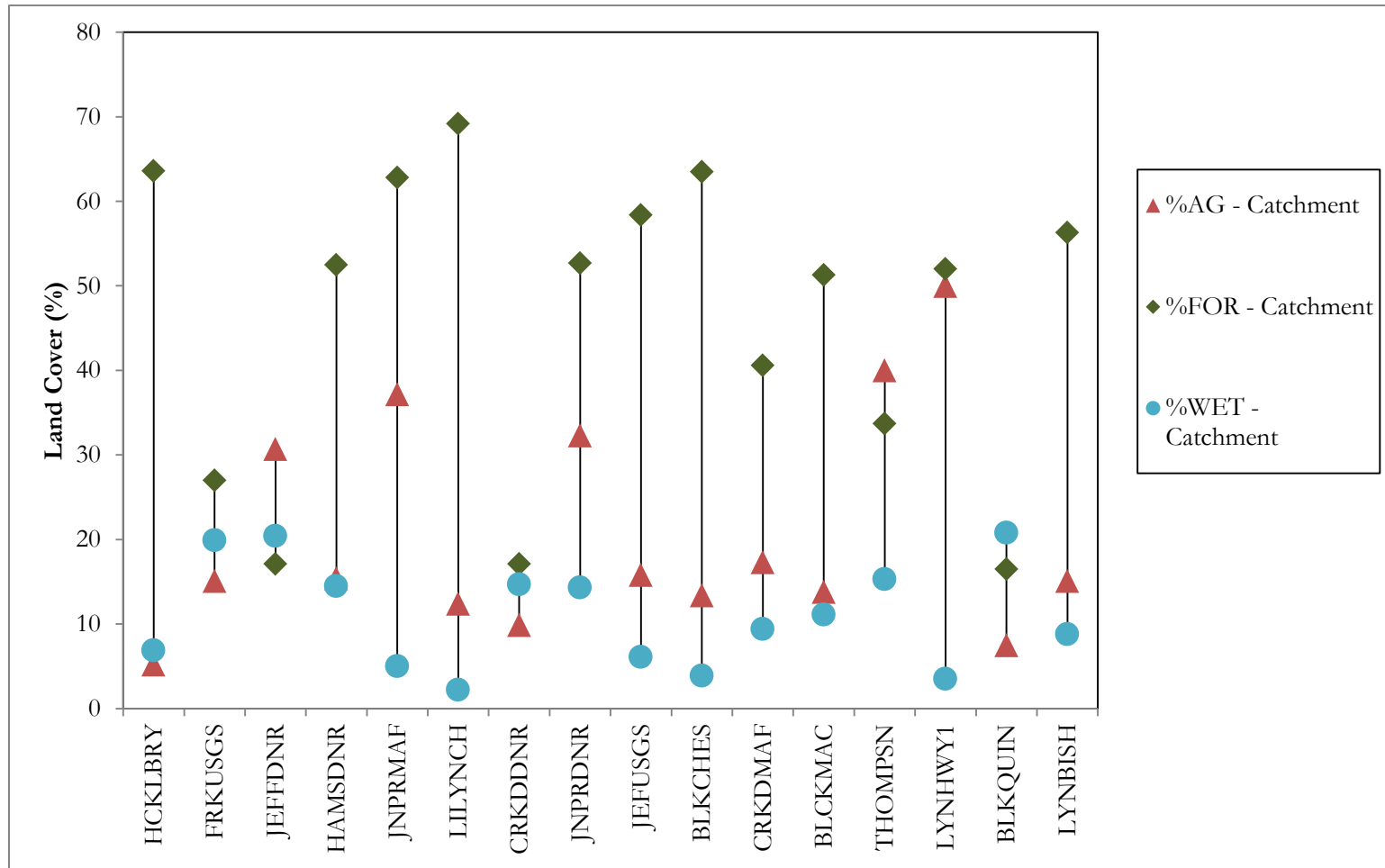


Figure 4.4d – Comparison of land cover types in each of the watersheds at a catchment scale. Each point shape represents a different land cover category (% Wetlands, % Forested, % Agriculture).

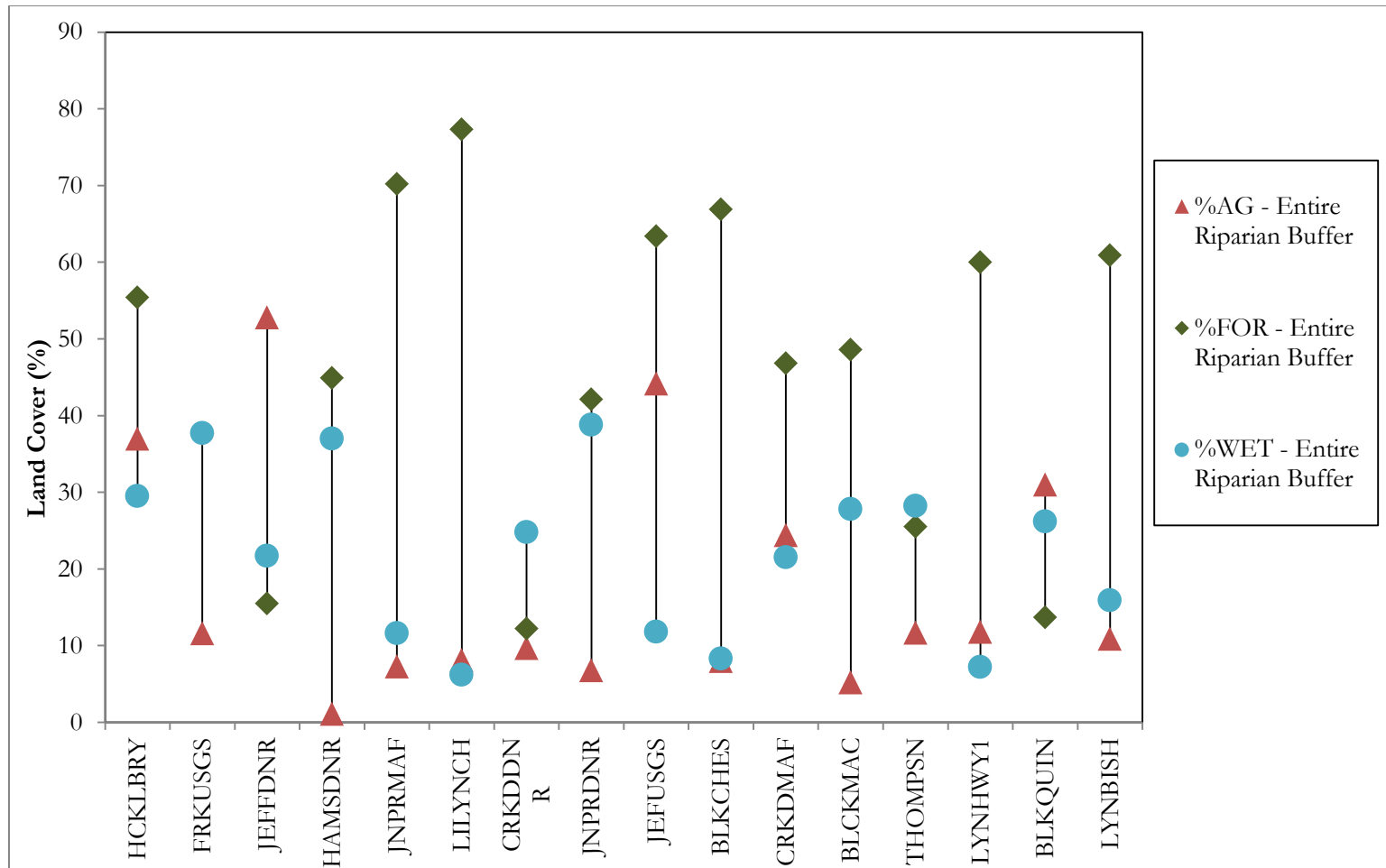


Figure 4.4e – Comparison of land cover types in each of the watersheds within the entire riparian buffer. Each point shape represents a different land cover category (% Wetlands, % Forested, % Agriculture).

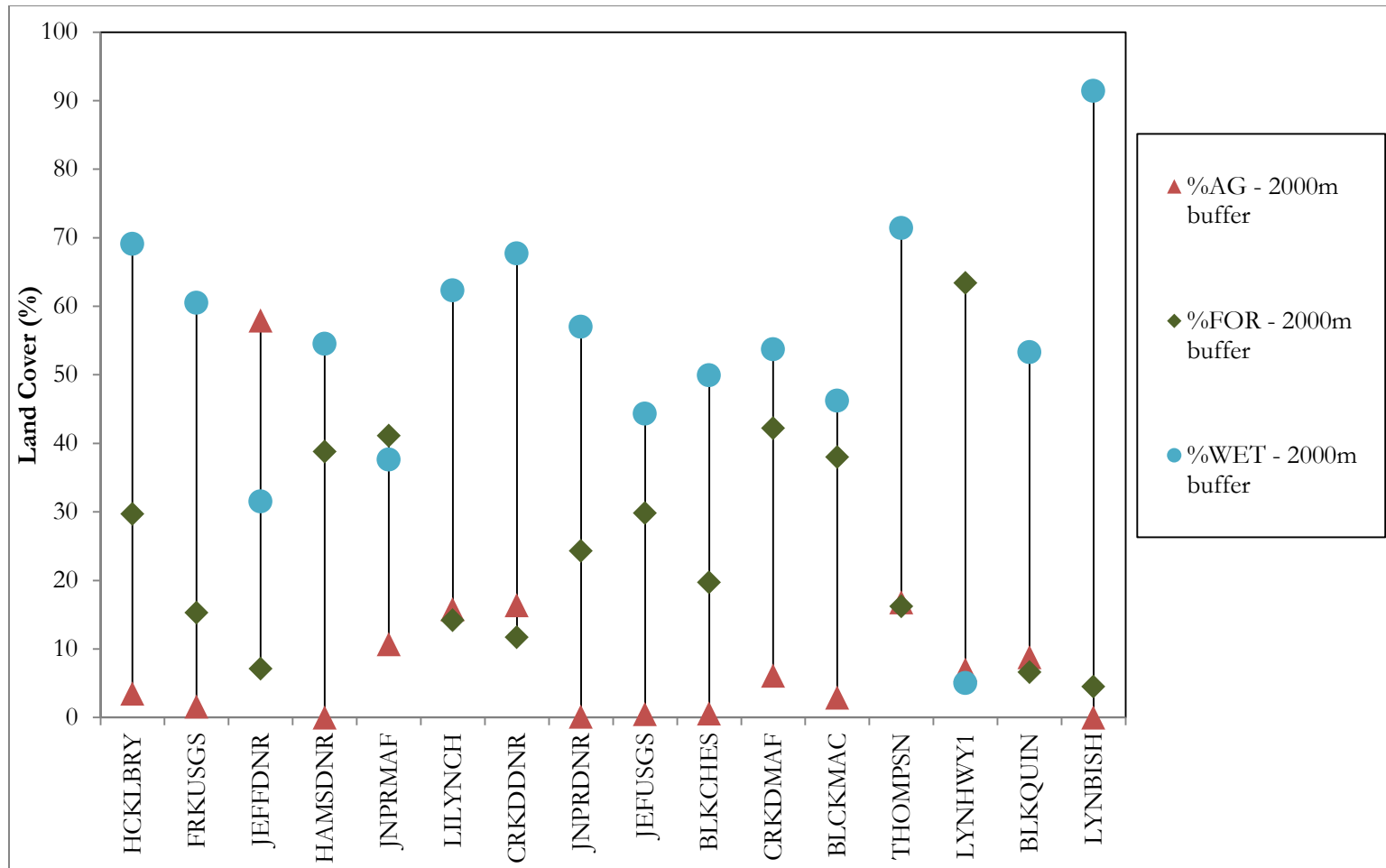


Figure 4.4f – Comparison of land cover types in each of the watersheds within 2000 m buffer. Each point shape represents a different land cover category (% Wetlands, % Forested, % Agriculture).

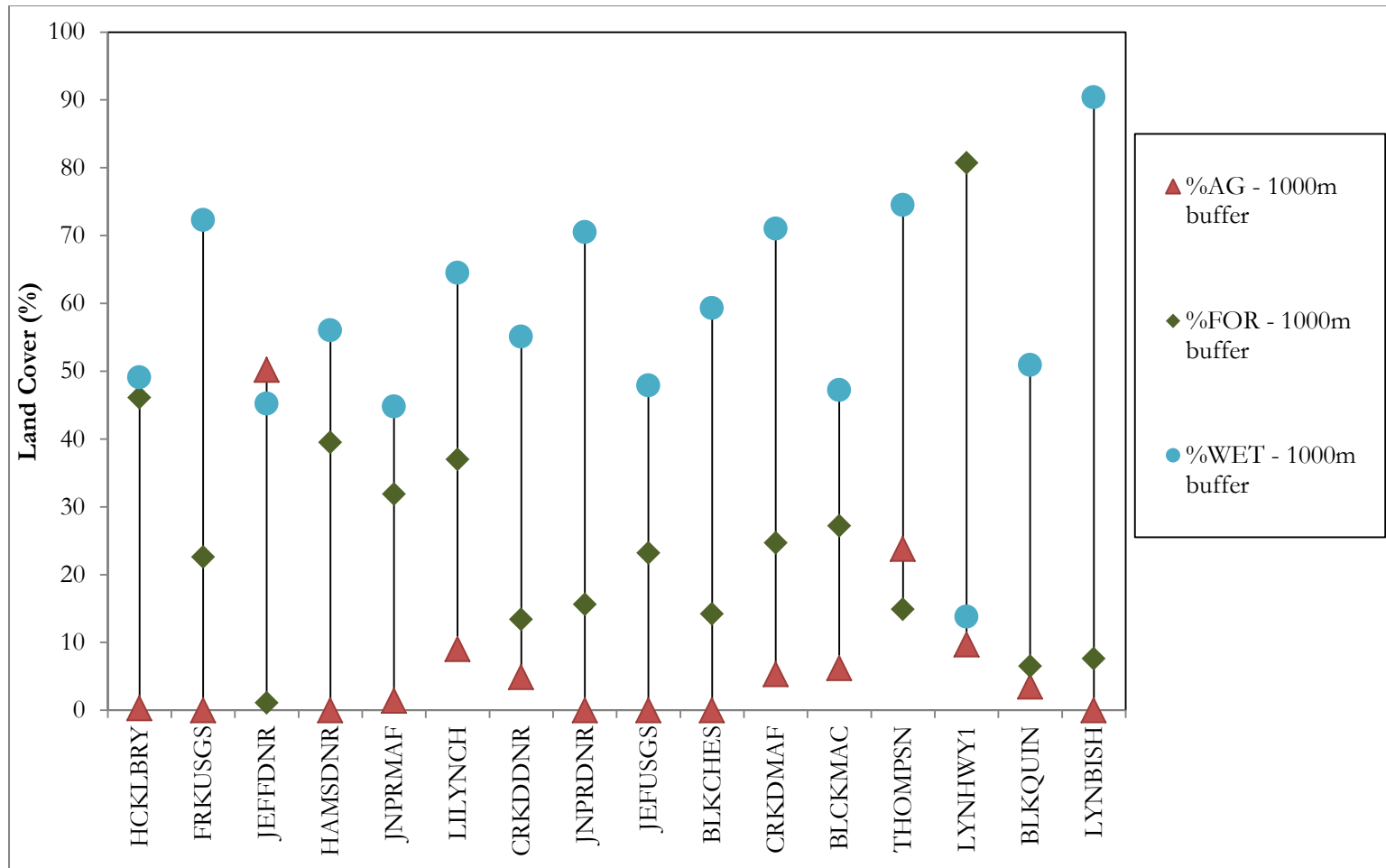


Figure 4.4g – Comparison of land cover types in each of the watersheds within 1000 m buffer. Each point shape represents a different land cover category (% Wetlands, % Forested, % Agriculture).

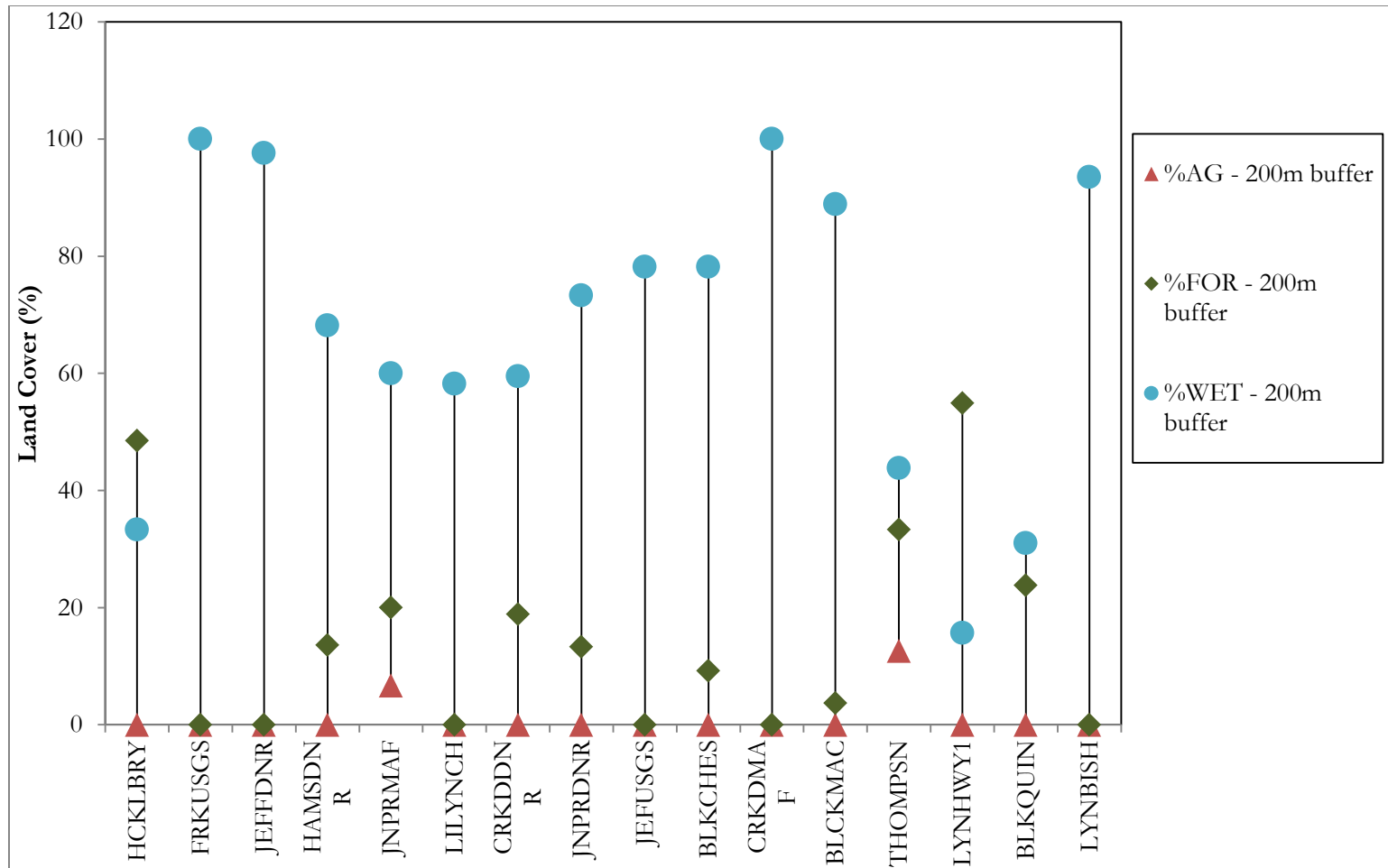


Figure 4.4h – Comparison of land cover types in each of the watersheds within 200 m buffer. Each point shape represents a different land cover category (% Wetlands, % Forested, % Agriculture).

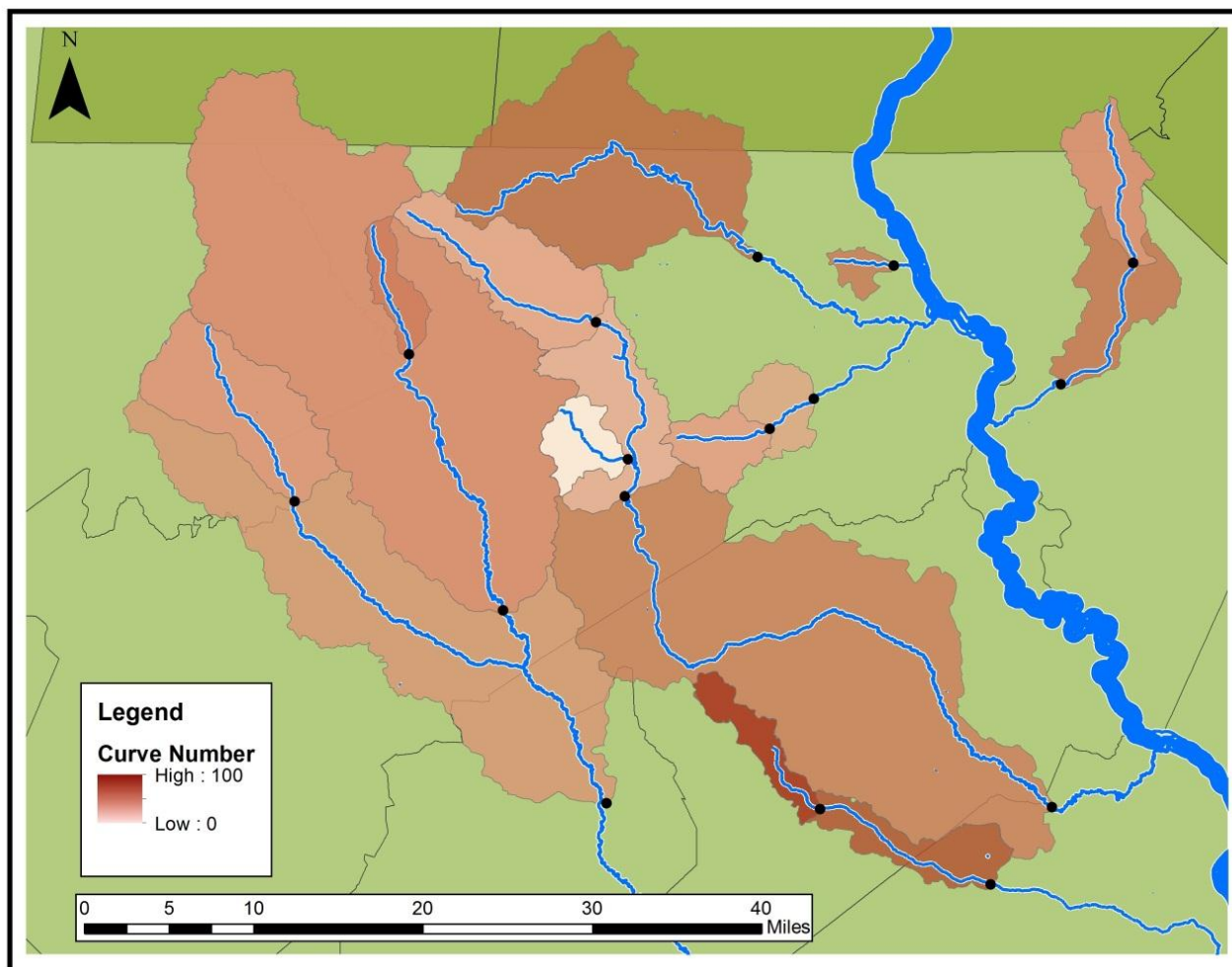


Figure 4.5a – Curve Numbers of watersheds monitored by SCPDP. Darker watersheds represent higher curve numbers. Black points represent the sampling sites and blue lines represent a simplification of the NHD.

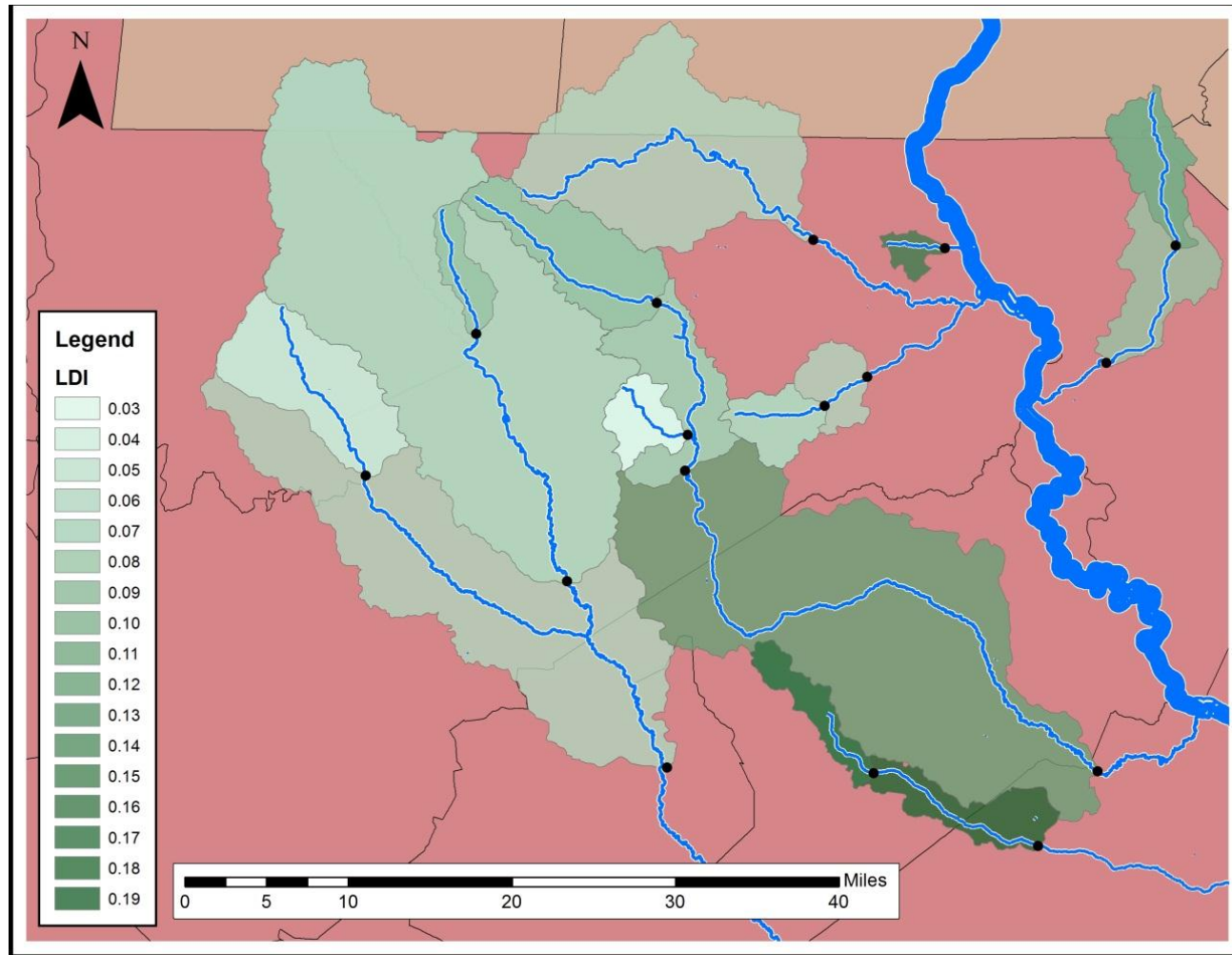


Figure 4.5b – Land Disturbance Index of watersheds monitored by SCPDP. Darker watersheds represent higher LDI with the highest LDI being 0.19. Black points represent the sampling sites and blue lines represent a simplification of the NHD.

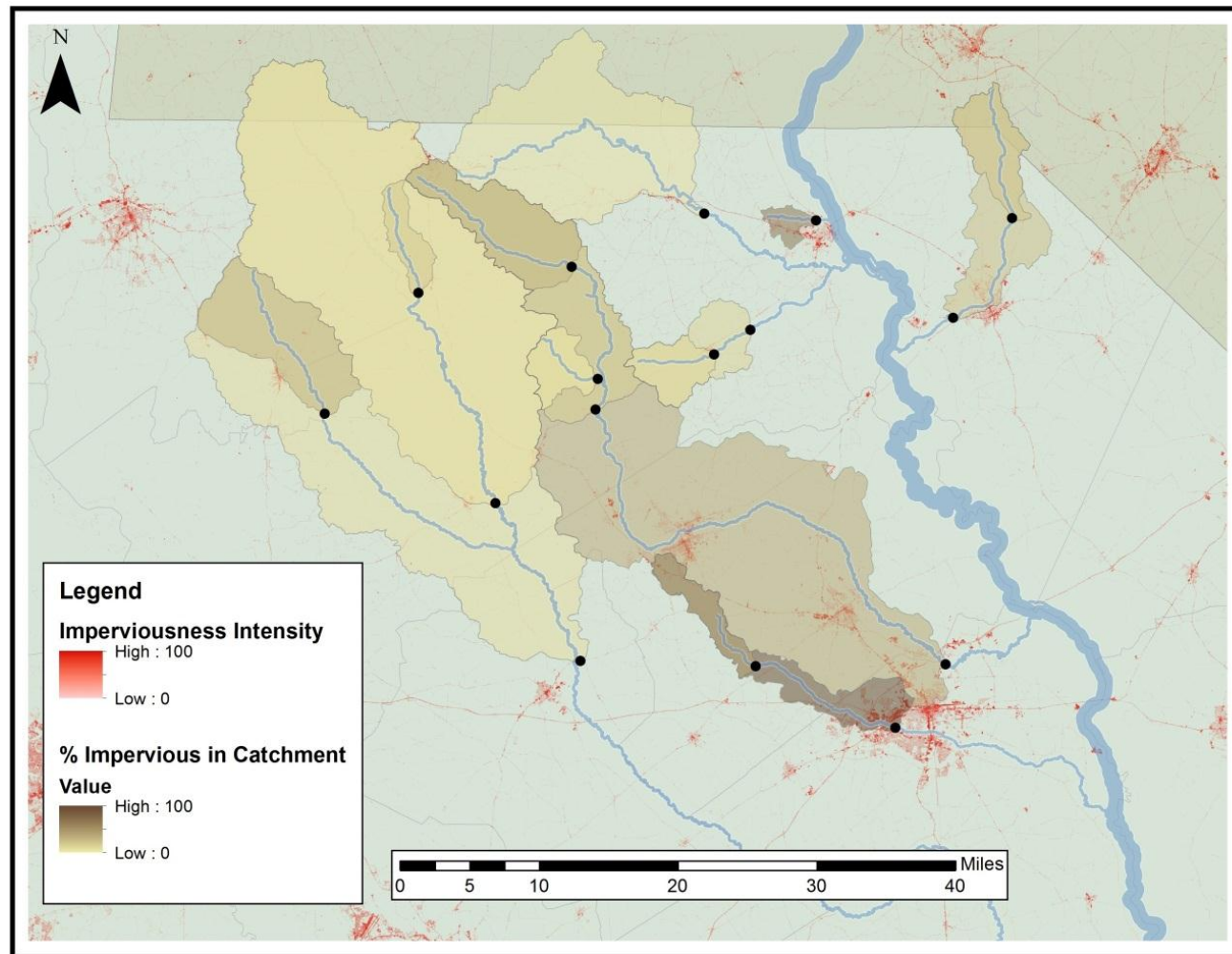


Figure 4.5c – Total Impervious Area of watersheds monitored by SCPDP. Darker watersheds represent higher TIA, while the varying shades of red represent the TIA in individual 30 m-by-30 m pixels in the watershed, with the darkest red being the most impervious (100%). Black points represent the sampling sites and blue lines represent a simplification of the NHD.

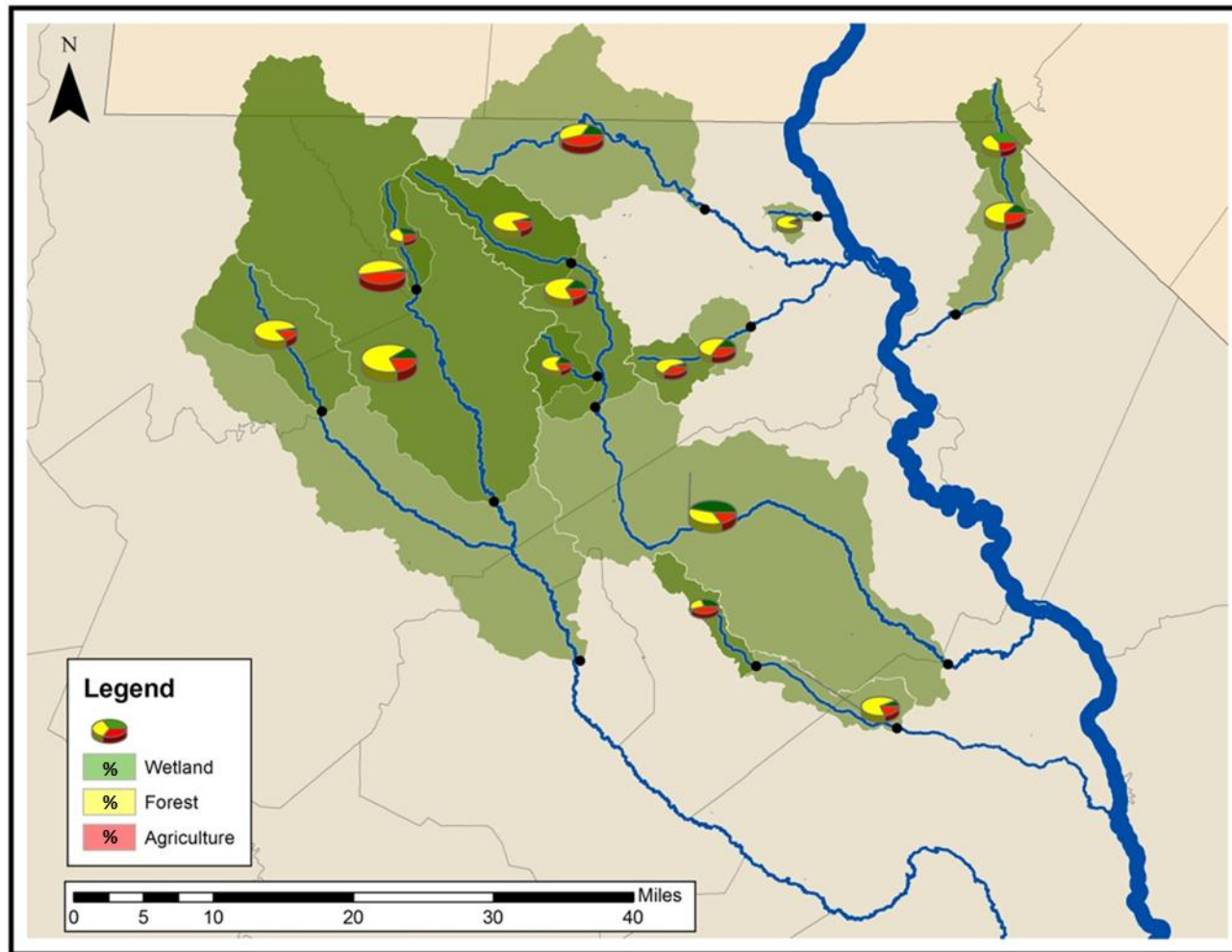


Figure 4.5d – Land cover distribution in watersheds monitored by SCPDP. Varying shades of green in the watershed only is for visualization, while overlaid pie charts represent the distribution of 3 of the most prominent land cover classes within each watershed. They do not add to 100%, but are to distinguish the dominating land cover of each watershed. Varying pie chart size is defined relative to watershed size.

4.2 FLUVIAL GEOMORPHOLOGY

Field measurements of cross section and profile were taken and imported into the reference reach spreadsheet (Mecklenburg and Ward, 2009). An example output of hydraulic geometry can be found in Figure 4.5a-c. All other graphical cross-sections and profiles can be found in Appendix C1.

Bankfull values were noted in the field and verified using the cross sectional data. Hydraulic geometry and bankfull depth (using the determined, verified bankfull) were derived from the 16 cross-sections and profiles. Slopes (S) ranged from nearly ponded (2×10^{-5} %) to relatively steep (0.42 %). Manning's roughness (n) had a wide variability, but stayed within the bounds of 0.038 to 0.107 that occur in literature (Chow, 1959), keeping in mind that many of these streams were swampy, sluggish, and highly impeded by large woody material. Hammer numbers (H) (Pizzuto et al., 2000) ranged from 1.1 to 11.0, where most values (>70%) fell between 2 and 5 and the average value was 4.3. Bankfull measurements of top width (W_{bkt}), average depth (D_{bkt}), cross sectional area (A_{bkt}) and flow rate (Q_{bkt}) varied greatly across multiple watershed scales. Top width (bankfull width) ranged from 12 to 161 ft, average depth ranged from 1.8 to 10.9 ft, cross sectional area ranged from 22 to 1743 ft², and bankfull flow rate varied between 20.7 and 2408 cfs. Recall that these are strictly bankfull values and that in many cases much larger flows were recorded that well exceeded these reported values. Due to the range of watershed areas, the hydraulic geometry and flow rate are better summarized in a table where each can be compared to its' respective drainage area. A complete summary of watershed area and bankfull geometry values can be found in Figures 4.7a-d and in Table 4.2.

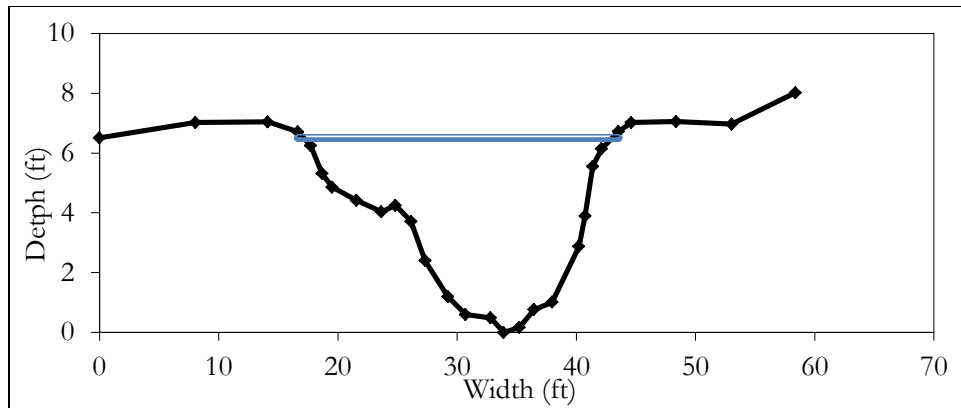


Figure 4.6a – Example of cross sectional data from Juniper Creek (DNR). The boxes represent discrete topographic measurements while the line represents an interpolation of the bed surface. The thick blue line signifies the best estimate of bankfull stage.

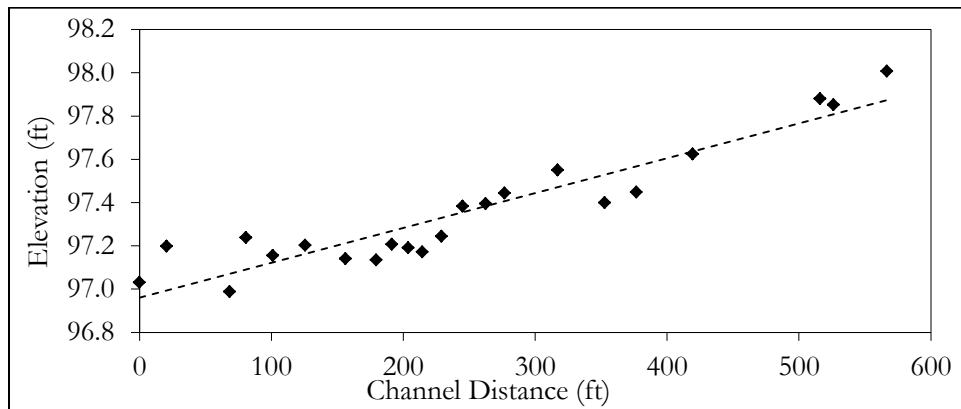


Figure 4.6b – Example profile data from Juniper Creek (DNR). The dotted line represents the slope of the water while the “+” marks represent the measured water level. This was measured from an arbitrary datum.

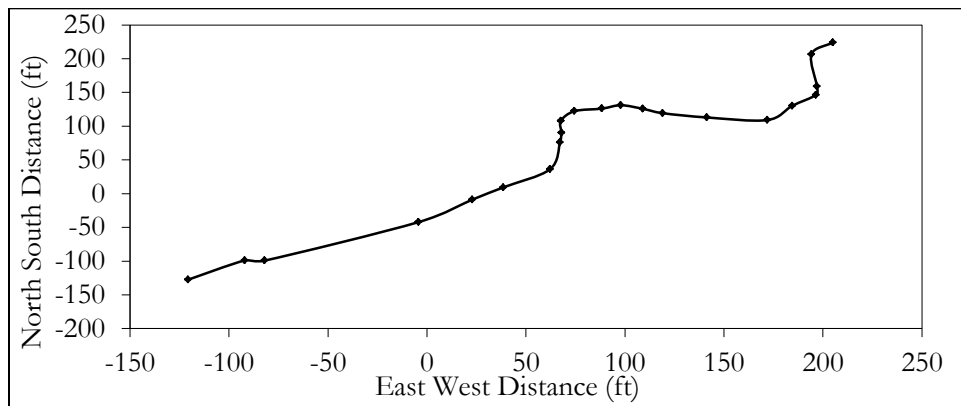


Figure 4.6c – Example sinuosity data from a single study site, Juniper Creek (DNR). The points represent individual measurements while the solid line represents the interpolated thalweg pattern.

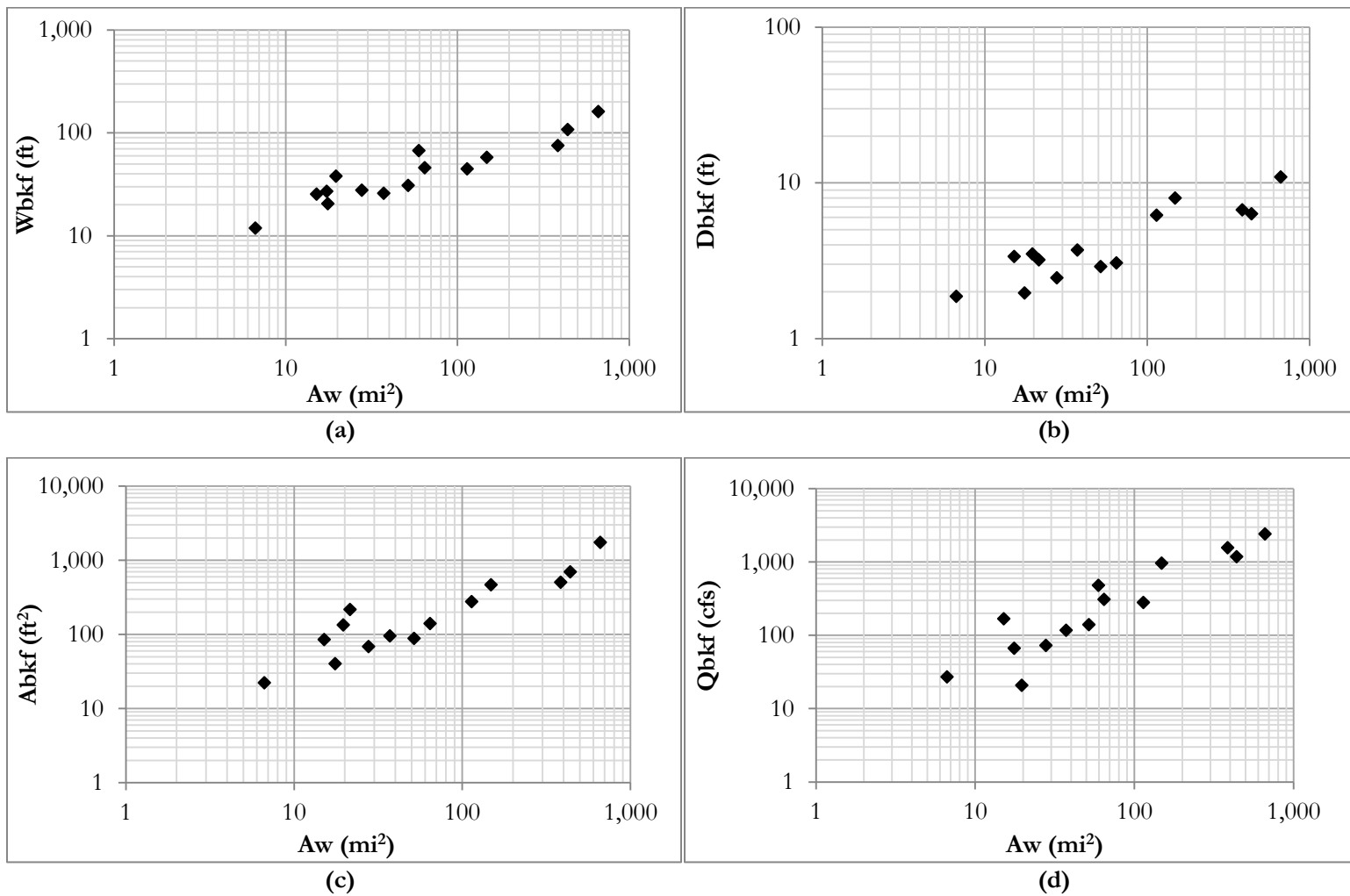


Figure 4.7 – Log_{10} transformed scatterplots showing variation of bankfull geometry with drainage area: (a) average bankfull width, (b) average bankfull depth (c) average bankfull cross sectional area and (d) average bankfull flow.

Table 4.2 – Summary of hydraulic geometry and other associated data for all monitored watersheds in the Pee Dee region.

Site Name	A _w (mi ²)	A _{bkf} (ft ²)	W _{bkf} (ft)	D _{bkf} (ft)	Q _{bkf} (cfs)	S (%)	Manning's n	H	Period of Record (years)
HCKLBRY	6.7	22.3	11.9	1.9	27	0.420	0.106	4.1	2.0
FORUSGS	15.2	85.6	25.4	3.4	168	0.280	0.086	11.0	2.5
JEFFDNR	17.3	-	-	-	-	2x10 ⁻⁵	-	-	2.0
HAMSDNR	17.6	40.2	20.5	2.0	66	0.200	0.076	3.8	2.0
JNPRMAF	19.7	134.2	37.9	3.5	21	2.3x10 ⁻³	0.089	1.1	2.0
LILYNCH	21.6	216.6	67.1	3.2	479	0.140	0.065	8.0	2.0
CRKDDNR	27.9	68.3	27.2	2.5	72	0.069	0.066	2.6	2.0
JNPRDNR	37.2	95.4	25.9	3.7	117	0.170	0.089	3.2	2.0
JEFUSGS	46.8	-	-	-	-	0.200	-	-	2.5
BLKCHES	51.8	88.3	30.8	2.9	139	0.064	0.050	2.7	7.0
CRKDMAF	64.6	139.9	45.7	3.1	309	0.110	0.046	4.8	2.0
BLCKMAC	114.1	276.2	44.7	6.2	281	0.024	0.068	2.5	52.0
THOMPSN	148.7	465.3	57.9	8.0	966	0.056	0.056	6.5	2.0
LYNHWWY1	385.4	505.8	75.3	6.7	1566	0.032	0.038	4.1	2.0
BLKQUIN	439.0	695.5	108.0	6.3	1180	0.140	0.107	2.7	10.0
LYNBISH	663.3	1742.5	160.6	10.9	2408	0.029	0.078	3.6	9.5

Measures marked with a “-” indicate that ponding at these sites resulted in the inability to accurately determine these dimensions.

Panoramic photos taken at each site helped to corroborate selection of bankfull stage and provided photographic documentation of each site. Evidence of bankfull included significant change in grade (i.e. steep slope to mild slope), change in vegetation (bare soil to grasses, grasses to moss, or the line where woody vegetation begins), significant changes in particle size (gravel to sand, sand to silt, etc.), level of organic debris (i.e. leaf litter), or scour lines (Dunne and Leopold, 1978). Because bankfull is an inherently “fuzzy” number (Johnson and Heil, 1996), evidence of all these factors were weighed against each other and an *estimate* of bankfull was made that satisfied as many indicators as possible. Figure 4.8 provides an example. As can be seen, this level satisfied the following criteria: 1) a significant change in slope, 2) a change in vegetation (the presence of both grass and woody vegetation), and 3) the presence of organic debris. Because of the swampy and sluggish nature of this

stream, there was not a significant change in bed substrate that occurred, nor were there scour lines. The remainder of panoramic photos used to verify bankfull can be referenced in Appendix C2.

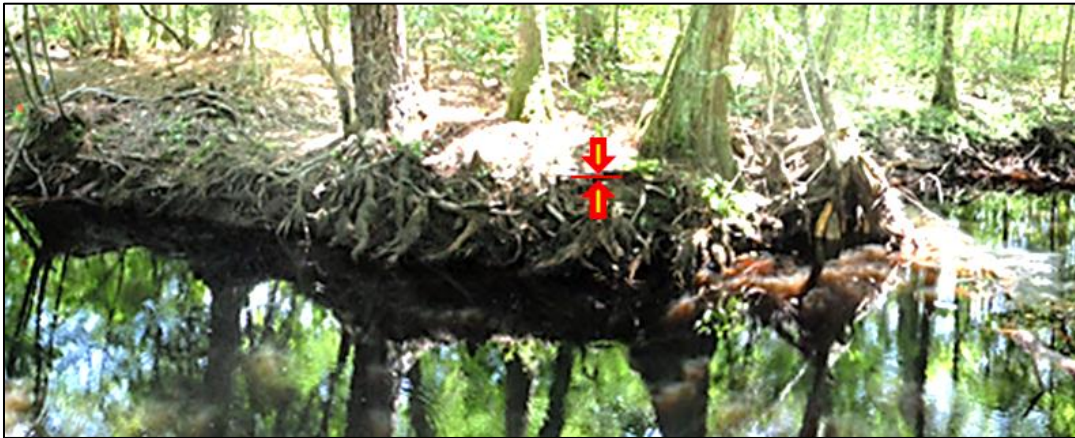


Figure 4.8 – Juniper Creek (DNR) panorama. The red and yellow arrows point to a line that was determined to be the approximate bankfull at this sampling site using the indicators mentioned in the paragraph above.

D_{16} ranged from 0.057 mm to 0.469 mm, D_{50} ranged from 0.304 mm to 36.709 mm, D_{84} ranged from 0.586 mm to 58.237 mm, and gradation coefficient ranged from 1.3 to 55.6. While the largest of D_{50} , D_{84} , and gradation coefficient all occurred within Huckleberry Branch, the smallest site, there was an even distribution of these variables between streams at the remaining sites (Table 4.3). Specific measurements from each site of D_{16} , D_{50} , D_{84} , and gradation coefficient (σ) are included in Table 4.3.

Distributions of D_{16} , D_{50} , and D_{84} , of the raw bed material dataset can be found in Figure 4.9.

However, it can be seen in Figure 4.9 that the presence of the extreme outliers created a particularly non-normal dataset.

Table 4.3 – D_{16} , D_{50} , D_{84} , and σ of characteristic bed material in a stream. These are average values of 5 samples taken across the nearest riffle to the stage recorder and the within bankfull of a single channel (braided channels were not sampled).

Site Name	A_w (mi ²)	D_{16} (mm)	D_{50} (mm)	D_{84} (mm)	Gradation Coefficient (σ)
HCKLBRY	6.68	0.335	36.709	58.237	55.6
FORUSGS	15.16	0.406	1.031	3.813	3.1
JEFFDNR	17.33	0.127	0.492	1.277	3.2
HAMSDNR	17.61	0.139	0.304	1.576	27.0
JNPRMAF	19.66	0.130	0.487	1.346	3.3
CRKDDNR	27.85	0.141	0.322	0.590	2.1
JNPRDNR	37.25	0.152	0.325	0.586	2.0
JEFUSGS	46.76	0.145	0.704	1.582	3.6
BLKCHES	51.77	0.469	0.486	0.775	1.3
CRKDMAF	59.66	0.190	0.427	4.230	6.1
LILYNCH	64.63	0.419	0.784	1.208	1.7
BLCKMAC	114.13	0.200	0.535	1.101	2.4
THOMPSN	148.66	0.459	0.929	1.928	2.1
LYNHwy1	385.44	0.292	0.528	1.131	2.0
BLKQUIN	439.03	0.122	0.323	0.619	2.3
LYNBISH	663.27	0.057	0.306	0.894	4.3

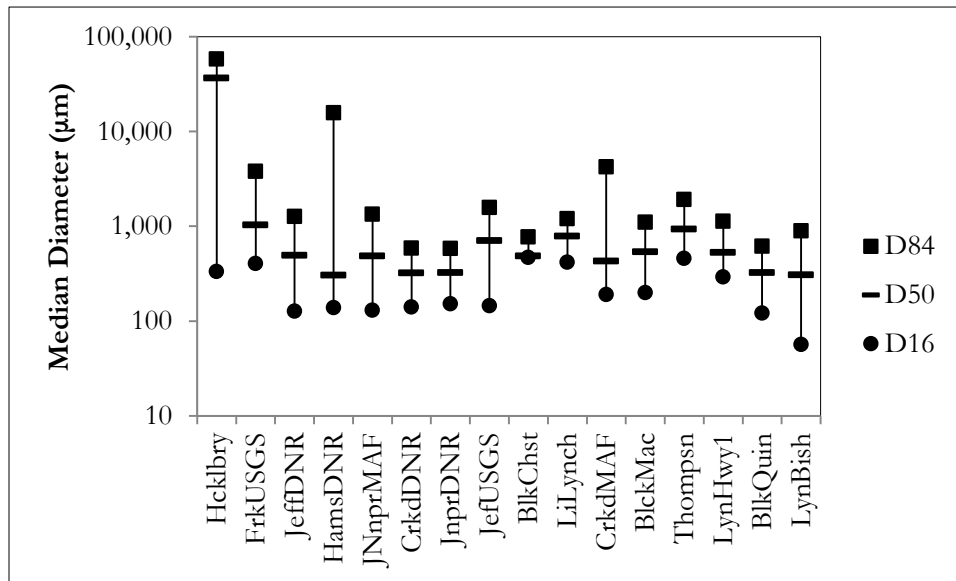


Figure 4.9 – Plot bed material (D_{16} , D_{50} , and D_{84}) for all sites before the removal of extreme outliers.

Outliers in the bed material dataset included both D_{50} and D_{84} at Huckleberry Branch and D_{84} at Hams Creek. All outliers fell above the outer fence, where the number of standard deviations from the median is greater than 3. Therefore these are classified as extreme outliers. Upon removal of the extreme outliers, the 16 original sites are shown in the Figure 4.10.

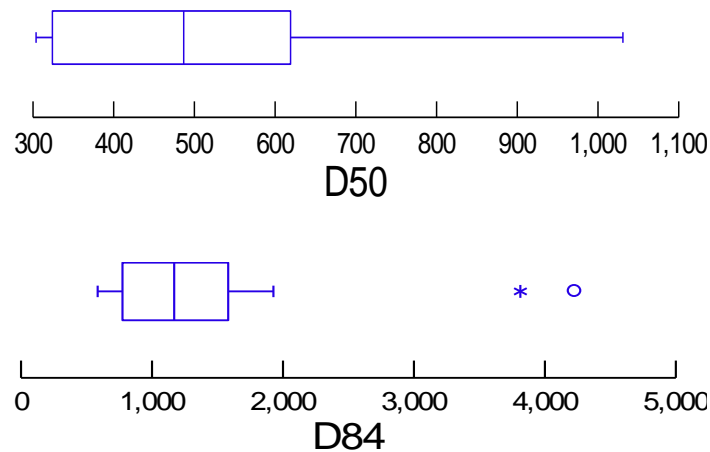


Figure 4.10 – Box and whisker plots of D_{50} and D_{84} upon the removal of extreme outliers present in Figure 4.8 at Hams Creek (D_{84}) and Huckleberry Branch (D_{50} and D_{84}). This dataset could now be normalized using a \log_{10} transform.

4.3 HYDROLOGY

Flow monitoring at these sites over a 2-to-52-year period provided insight into variations in stream flow. Extant continuous data from each site was compiled into a hydrograph of daily averages. A sample dataset is outlined in Figure 4.11, and all other flow data have been compiled in Appendix C3. At all sites except those operated by USGS, temperature was also recorded. A sample of a single dataset of daily and weekly averages is found in Figure 4.12.

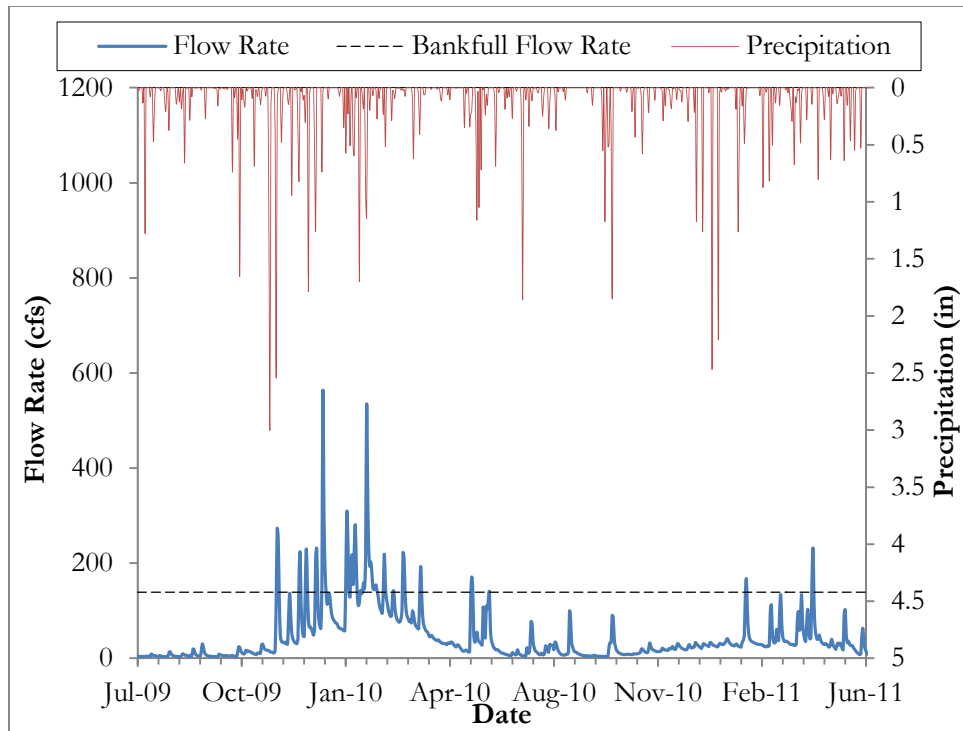


Figure 4.11 – Example of flow data derived from flow stage, cross-section, and slope. This was the period of record from Black Creek below Chesterfield (USGS). Bankfull flow marked with the dotted black line. Precipitation data is indicated on the secondary axis.

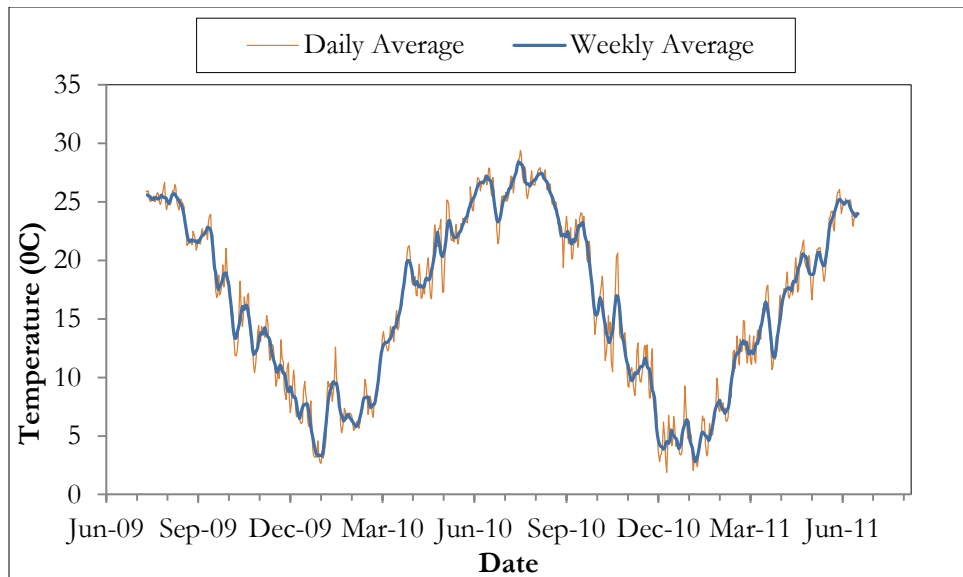


Figure 4.12 – Example daily temperature data (orange) and moving weekly average used in the calculation of TVI at Huckleberry Branch. Similar temperature profiles for the remaining 9 sites where water temperature was recorded can be referenced in Appendix C4.

Bankfull occurrence ranged from 0 to almost 9 times per year with an average of 3.4 across all watersheds, while Richards-Bake Flashiness (Baker et al., 2004) varied between 0.10 and 0.52 with an average of 0.25. A method to quantify stream temperature variation (TVI) ranged from 0.38 to 0.88. Crooked Creek had the greatest TVI while Jeffries Creek (DNR) had the lowest. Generally, TVI ranged from 0.5-0.6 (the average was 0.64). Average annual bankfull occurrence, RBI, and TVI are summarized in Table 4.4.

Table 4.4 – Richards-Baker Flashiness (RBI), bankfull occurrence (Bkf/yr), and the temperature variation index (TVI) at each site. Recall that no temperature data is available for USGS sites; hence, they are marked with a dash.

Site Name	Bkf/yr	RBI	TVI	Pd. of Record (yrs.)
HCKLBRY	2.09	0.10	0.78	2.0
FORUSGS	0.65	0.41	-	2.5
JEFFDNR	-	-	0.43	2.0
HAMSDNR	3.67	0.24	0.55	2.0
JNPRMAF	4.23	0.12	0.84	2.0
LILYNCH	3.80	0.18	0.61	2.0
CRKDDNR	8.94	0.10	0.80	2.0
JNPRDNR	-	0.30	-	2.5
JEFUSGS	6.98	0.31	-	7.0
BLKCHES	2.58	0.52	0.48	2.0
CRKDMAF	1.63	0.14	0.88	2.0
BLCKMAC	6.38	0.14	-	52.0
THOMPSN	0.00	0.56	0.64	2.0
LYNHWWY1	3.64	0.32	0.38	2.0
BLKQUIN	1.52	0.11	-	10.0
LYNBISH	1.89	0.21	-	9.5
Average Values	3.43	0.25	0.64	

4.4 BEDLOAD ESTIMATES

Using the results from the previous three sections, theoretical bed loads were calculated by utilizing Brownlie's equations (Brownlie, 1981). Bed load divided by watershed area, and reported on a per-year basis ($BL/A_w * yr$) with result in a ranging from 0.05 ton/mi²*yr (Juniper Creek) to 190 tons/mi² yr (Hams Creek DNR), and an average of 55 tons/mi²*yr. An example daily bed load flux can be found in Figure 4.13 and all other values in Table 4.5. All other bed daily bed loads can be found in Appendix C5.

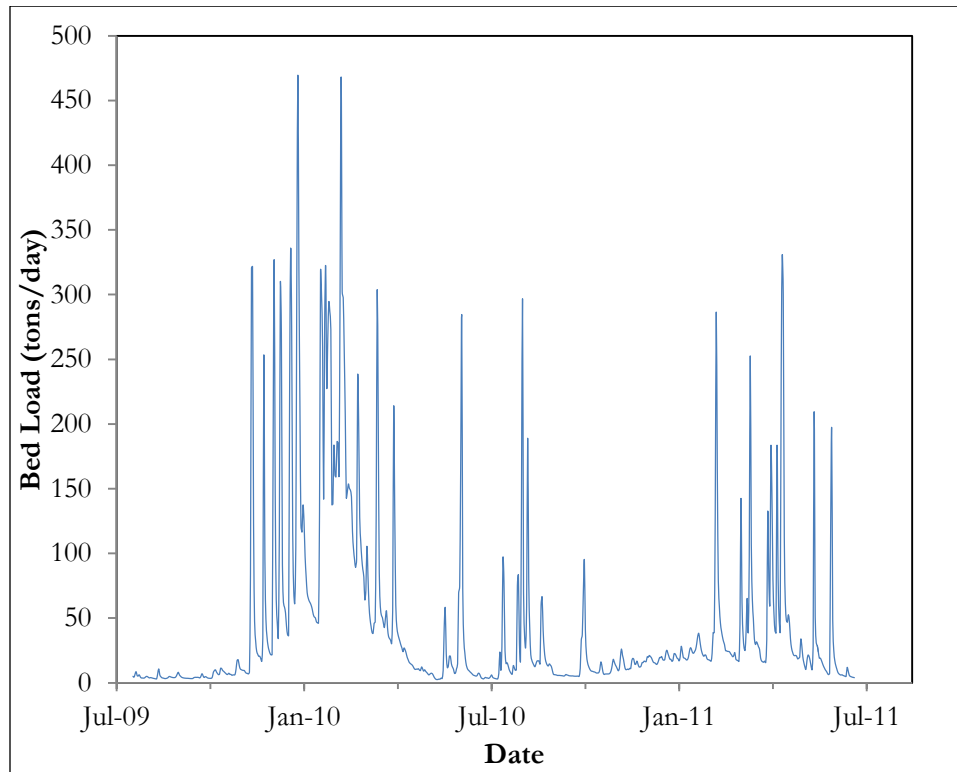


Figure 4.13 – Bed load flux (daily) of Lynches River. The area under this curve was summed to yield total bedload flux over the period of record, then converted to an annual average.

Table 4.5 – Annual estimated bedload yield and annual bedload yields normalized by watershed area, per year for each sample site.

Site Name	BL/yr (tons/yr)	BL/A _w *yr (tons/yr*mi ²)
HCKLBRY	339	51
FORUSGS	681	45
JEFFDNR	-	-
HAMSDNR	3,343	190
JNPRMAF	1	0.05
LILYNCH	1,518	25
CRKDDNR	1,056	38
JNPRDNR	603	16
JEFUSGS	-	-
BLKCHES	2,799	54
CRKDMAF	9,369	145
BLCKMAC	1,703	15
THOMPSN	1,647	11
LYNHWY1	16,583	43
BLKQUIN	55,202	126
LYNBISH	7,760	12

Site with downstream obstruction to flow that resulted in the inability to reliably determine bankfull elevation are marked with a “-”

4.5 STATISTICAL ANALYSIS

Log₁₀-transformation of some datasets yielded normally distributed data. Log₁₀-transformed datasets included all bankfull geometry, soil data and H. Richards-Baker Flashiness Index (RBI), slope, and annual bed load flux divided by watershed area (BL_{yr}/A_w) was normalized using a square root transformation. Land cover measurements were very different depending upon scale, and thus, transformations were based on scale (*200 m, 1000 m, 2000 m, and entire riparian buffers, and catchment*) and land cover indicator (% agriculture, % forested, % wetland, % impervious, LDI, CN, etc.). Even after performing log₁₀ and square root transformations, three datasets proved to be non-normal (%

agriculture at the 200 m and 1000 m buffer scales, and LDI at the entire buffer scale). Other accepted transformations highlighted by McCune and Grace (2002) were attempted, including power transformations, arcsine transformations, and arcsine square root transformations, but did not yield normalized results. With all aforementioned efforts, two datasets (Agriculture at the 200 *m* and 1000 *m* buffer scales) remained non-normal and were omitted from the remainder of analysis. Each of the normalized parameters can be referenced in Table 4.6 with the associated transformation and Anderson-Darling p-value.

Table 4.6a – Summary of normalized variables (Anderson-Darling P-Value >0.05), including number of cases and omitted values. This table is color-coded to express the many different facets of this study as components of stream flow function (blue), stream geomorphology (orange), and characteristic bed material (green).

Variable	Transform Used	Anderson - Darling p-value	# Cases	Outliers	Missing Values
QHEI	-	>0.15	16	-	-
RBI	Sq. rt.	>0.15	15	-	JEFFDNR
H	Log ₁₀	0.084	14	-	JEFFDNR, JEFUSGS
Bkf/yr	-	>0.15	14	-	JEFFDNR, JEFUSGS
BL _{yr} /A _w	Sq. rt.	>0.15	14	-	JEFFDNR, JEFUSGS
TVI	-	>0.15	10	-	All USGS sites (6)
A _w	Log ₁₀	>0.15	16	-	-
S	Sq. rt.	>0.15	16	-	-
W _{bkf}	Log ₁₀	>0.15	15	-	JEFUSGS
D _{bkf}	Log ₁₀	>0.15	15	-	JEFUSGS
A _{bkf}	Log ₁₀	>0.15	15	-	JEFUSGS
Q _{bkf}	Log ₁₀	>0.15	14	-	JEFFDNR, JEFUSGS
n	-	>0.15	14	-	JEFFDNR, JEFUSGS
D ₁₆	Log ₁₀	0.098	16	-	-
D ₅₀	Log ₁₀	>0.15	15	HCKLBRY	-
D ₈₄	Log ₁₀	>0.15	14	HCKLBRY, HAMSCRK	-

Table 4.6b – Summary of normalized variables (Anderson-Darling P-Value >0.05) of analyzed land classes including number of cases and omitted values.

Variable	Transform Used	Anderson - Darling p-value	# Cases	Outliers
CN (200 m riparian buffer)	-	>0.15	16	-
CN (1000 m riparian buffer)	-	>0.15	16	-
CN (2000 m riparian buffer)	-	>0.15	16	-
CN (entire riparian buffer)	-	>0.15	16	-
CN (entire catchment)	-	>0.15	16	-
% Agriculture (2000 m riparian buffer)	Sq. rt.	>0.15	16	-
% Agriculture (entire riparian buffer)	Log ₁₀	>0.15	16	-
% Agriculture (entire catchment)	Log ₁₀	>0.15	16	-
% Forest (200 m riparian buffer)	Sq. rt.	0.095	16	-
% Forest (1000 m riparian buffer)	Sq. rt.	>0.15	16	-
% Forest (2000 m riparian buffer)	-	>0.15	16	-
% Forest (entire riparian buffer)	-	>0.15	16	-
% Forest (entire catchment)	-	0.12	16	-
% Wetland (200 m riparian buffer)	-	>0.15	16	-
% Wetland (1000 m riparian buffer)	-	>0.15	16	-
% Wetland (2000 m riparian buffer)	-	>0.15	16	-
% Wetland (entire riparian buffer)	-	>0.15	16	-
% Wetland (entire catchment)	-	>0.15	16	-
LDI (200 m riparian buffer)	Sq. rt.	>0.15	16	-
LDI (1000 m riparian buffer)	Log ₁₀	>0.15	16	-
LDI (2000 m riparian buffer)	Sq. rt.	0.141	16	-
LDI (entire riparian buffer)	-	>0.15	16	-
LDI (entire catchment)	Log ₁₀	0.111	16	-
% Impervious (200 m riparian buffer)	Sq. rt.	0.086	16	-
% Impervious (1000 m riparian buffer)	Log ₁₀	>0.15	15	CRKDDNR
% Impervious (2000 m riparian buffer)	Log ₁₀	>0.15	16	-
% Impervious (entire riparian buffer)	Log ₁₀	>0.15	16	-
% Impervious (entire catchment)	Log ₁₀	>0.15	16	-

4.5.1 Land Use

The statistical analyses between land cover data and indices of stream function (QHEI, RBI, bankfull occurrences per year, H, annual bed load flux, and TVI) resulted in three of the 180 relationships tested were above our assigned threshold of $R > 0.60$. These can be found in Table 4.7.

Table 4.7 – Correlations found between all land cover metrics and potential indicators of physical and/or ecological stability within the stream. Significant (<0.05) correlations are bolded and underlined.

	QHEI [†]	RBI [‡]	Bkf/yr [*]	H [§]	BL _{yr} /A _w [#]	TVI [@]
CN (200 m riparian buffer)	-0.09	0.53	-0.07	0.57	-0.24	-0.12
CN (1000 m riparian buffer)	-0.25	0.55	-0.30	<u>0.65</u>	-0.18	-0.36
CN (2000 m riparian buffer)	-0.29	0.60	-0.34	<u>0.62</u>	-0.30	-0.44
CN (entire riparian buffer)	-0.39	0.24	<u>-0.67</u>	0.48	-0.03	-0.20
CN (entire catchment)	-0.38	0.13	<u>-0.61</u>	0.32	-0.05	-0.01
% Agriculture (200 m riparian buffer)	-0.16	0.34	-0.31	-0.05	-0.46	0.20
% Agriculture (1000 m riparian buffer)	-0.23	0.49	-0.16	0.38	-0.13	-0.37
% Agriculture (2000 m riparian buffer)	-0.27	0.21	-0.40	0.02	-0.22	-0.36
% Agriculture (entire riparian buffer)	-0.41	-0.12	-0.43	0.14	-0.02	0.06
% Agriculture (entire catchment)	-0.32	0.28	0.17	-0.08	-0.41	-0.26
% Forest (200 m riparian buffer)	0.38	0.01	-0.35	0.37	0.46	0.50
% Forest (1000 m riparian buffer)	0.46	0.30	0.20	0.39	0.04	-0.13
% Forest (2000 m riparian buffer)	0.38	0.18	0.37	0.15	-0.11	-0.13
% Forest (entire riparian buffer)	0.03	<u>0.66</u>	-0.05	0.41	-0.35	-0.43
% Forest (entire catchment)	0.14	0.46	-0.01	0.29	-0.21	-0.17
% Wetland (200 m riparian buffer)	-0.19	-0.17	0.38	-0.47	-0.43	-0.12
% Wetland (1000 m riparian buffer)	-0.16	-0.33	0.00	-0.44	0.00	<u>0.63</u>
% Wetland (2000 m riparian buffer)	0.04	-0.42	-0.06	-0.31	0.27	<u>0.61</u>
% Wetland (entire riparian buffer)	0.16	<u>-0.83</u>	0.47	<u>-0.74</u>	0.15	<u>0.67</u>
% Wetland (entire catchment)	-0.20	<u>-0.71</u>	0.26	-0.62	0.13	0.40
LDI (200 m riparian buffer)	-0.37	0.05	-0.31	0.29	0.09	0.11
LDI (1000 m riparian buffer)	-0.38	0.17	-0.21	0.00	-0.06	-0.04
LDI (2000 m riparian buffer)	-0.50	0.30	-0.36	0.12	-0.29	-0.01
LDI (entire riparian buffer)	-0.17	-0.26	-0.33	-0.01	0.31	0.46
LDI (entire catchment)	-0.29	-0.33	-0.10	-0.21	0.05	0.15
% Impervious (200 m riparian buffer)	-0.39	0.00	-0.11	-0.07	-0.09	0.10
% Impervious (1000 m riparian buffer)	-0.45	-0.15	0.54	-0.27	-0.26	0.23
% Impervious (2000 m riparian buffer)	-0.53	0.36	0.00	0.18	-0.50	-0.13
% Impervious (entire riparian buffer)	-0.23	-0.25	-0.12	0.00	0.15	0.20
% Impervious (entire catchment)	-0.30	-0.14	-0.04	0.02	0.06	0.20

[†]Qualitative Habitat Evaluation Index, [‡]Richards-Baker Flashiness Index, ^{*}Bankfull occurrences per year, [§]Hammer Number, [#]Annual bedload divided by catchment area, [@]Temperature Variation Index

Correlations with a magnitude greater than $R = 0.7$ were found only within the percentage of wetland land cover classification, suggesting a particular importance of wetlands within these stream systems. Wetlands typically dominated the landscape at the three smallest scales of the riparian buffer (200 m, 1000 m, and 2000 m) while forested land cover dominated at the two largest scales (entire riparian and entire catchment). However, wetlands showed high correlations with RBI at the entire buffer and entire catchment scales ($R = -0.71$, $p = 0.003$ and $R = -0.83$, $p < 0.001$; respectively). Hammer number was also found to be significantly correlated to the percentage of wetlands in the entire riparian buffer ($R = -0.74$, $p = 0.003$).

For each of the correlated pairs with an above the threshold ($R > 0.7$) discussed in the Methods section (Section 3.9.2), linear regression analyses were performed. Richards-Baker Flashiness Index had a significant relationship with percentage wetland at the entire buffer scale ($R^2 = 0.69$, $p < 0.001$) as well as the catchment scale ($R^2 = 0.50$, $p = 0.003$), meaning that 69% and 50% of the variation in RBI could be explained by percent wetland in the entire riparian buffer and catchment scales, respectively. With the removal of an outlier ($|z| = 3.326$), the regression, 74% of the variation in RBI could be explained by percentage wetland at the catchment scale ($R^2 = 0.74$, $p < 0.001$). Percentage wetland at the 1000 m buffer scale was found to have a high explain 54% of the variation in TVI ($R^2 = 0.54$, $p = 0.035$). Scatter plots and the associated regression trend lines between the transformed datasets can be found in Figures 4.13, 4.14, and 4.15.

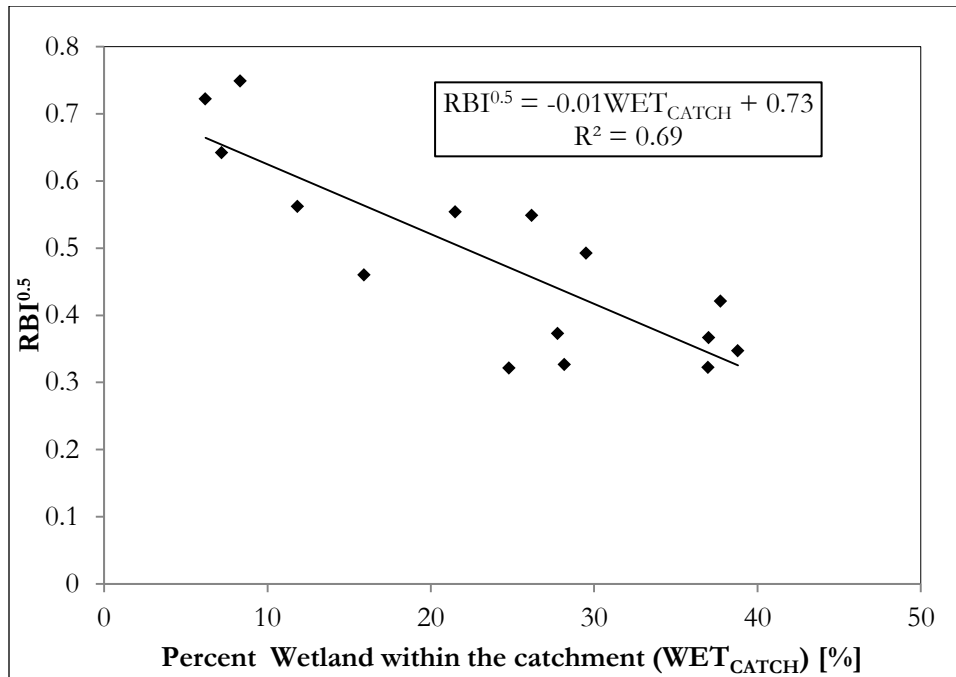


Figure 4.14 – Significant linear relationship between percentage of wetland within the catchment and the square root of RBI.

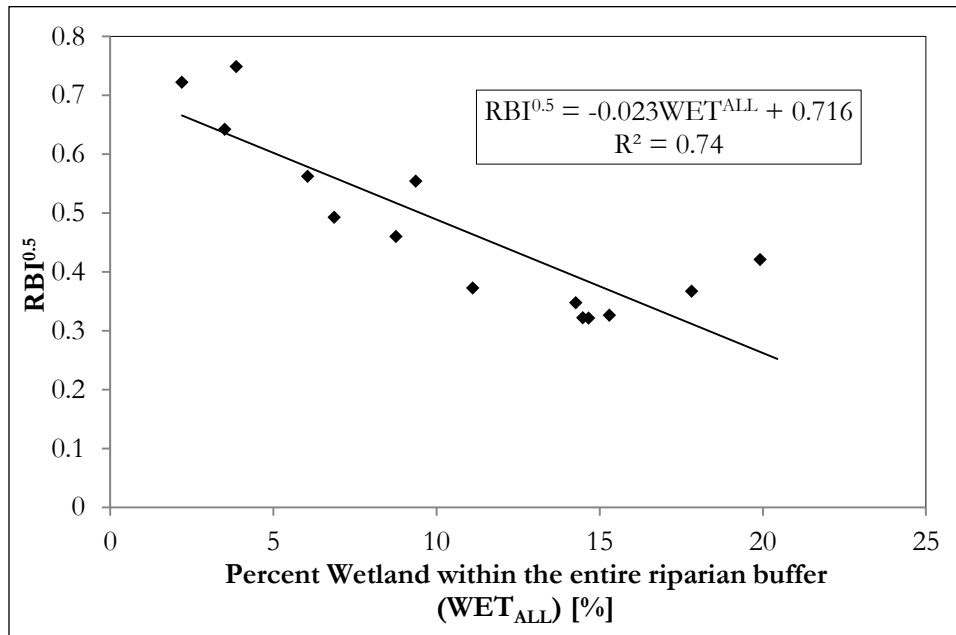


Figure 4.15 – Significant linear relationship between percentage of wetland within the entire riparian buffer and the square root of RBI.

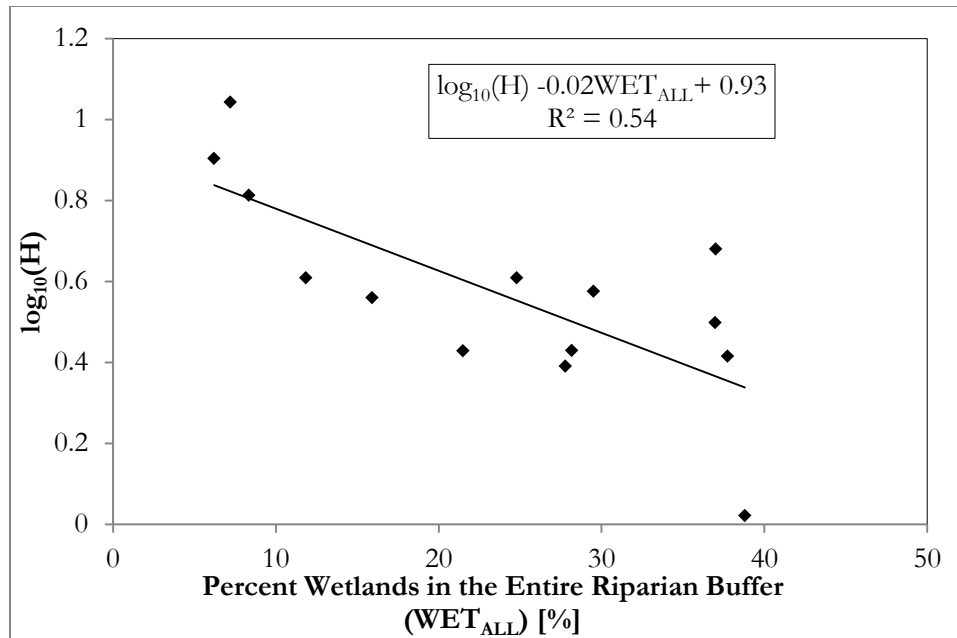


Figure 4.16 – Significant linear relationship between percentage of wetland within the entire riparian buffer and H.

Other correlations above the $R=0.6$ threshold, but below $R=0.7$ threshold used for regression analysis occurred between land cover and indices of stream function are worth mentioning. Curve Number at the entire riparian buffer and entire catchment scales were found to be correlated with the number of bankfull occurrences per year ($R=-0.67$, $p=0.009$; $R=-0.61$, $p=0.021$). Curve Number at the 1000 m and 2000 m riparian buffer scales was found to be positively correlated to Hammer number ($R=0.65$ and $R=0.62$, respectively, with p -values of 0.013 and 0.018), while the percentage of wetlands within the entire catchment was found to be negatively correlated to Hammer number ($R=-0.62$, $p=0.018$). Percentage of wetland within the 1000 m, 2000 m, and entire buffer scales were found to correlate to TVI ($R=0.63$, 0.61, and 0.67; respectively, with p -values of 0.049, 0.062, and 0.035). The other notable correlation found within the land cover category was the correlation between forested land cover at an entire riparian buffer scale and RBI ($R=0.66$, $p=0.007$).

4.5.2 Hydraulic Geometry

Correlations between log-transformed watershed area and log-transformed bankfull measurements of width, depth, cross sectional area, and flow rate were all found to be correlated ($R=0.93, 0.89, 0.95$, and 0.92 ; respectively, and p -values of <0.001 for each). Regression analyses yielded highly significant relationships ($p < 0.001$) between all bankfull measurements and watershed area and R^2 values between 0.75 and 0.88 . The resulting regional curves, in the form of the modified power function originally reported by Dunne and Leopold's (1974), are summarized below.

$$W_{bfl} = 6.30(A_w)^{0.46} \quad R^2 = 0.87 \quad (4.1)$$

$$D_{bkl} = 1.05(A_w)^{0.33} \quad R^2 = 0.75 \quad (4.2)$$

$$A_{bkf} = 6.67(A_w)^{0.79} \quad R^2 = 0.88 \quad (4.3)$$

$$Q_{bkf} = 3.83(A_w)^{0.99} \quad R^2 = 0.85 \quad (4.4)$$

Only 15 sites were used in the derivation of these relationships. Jeffries Creek (USGS) was omitted due to a downstream impoundment thought to significantly influence its' hydraulic geometry. Jeffries Creek (DNR) was also omitted from Figure 4.20 due to significant beaver activity immediately downstream of the site early in the study. However, bankfull measurements of width, depth, and area were conducted before the onset of beaver activity and thus are included in Figures 4.16-4.18.

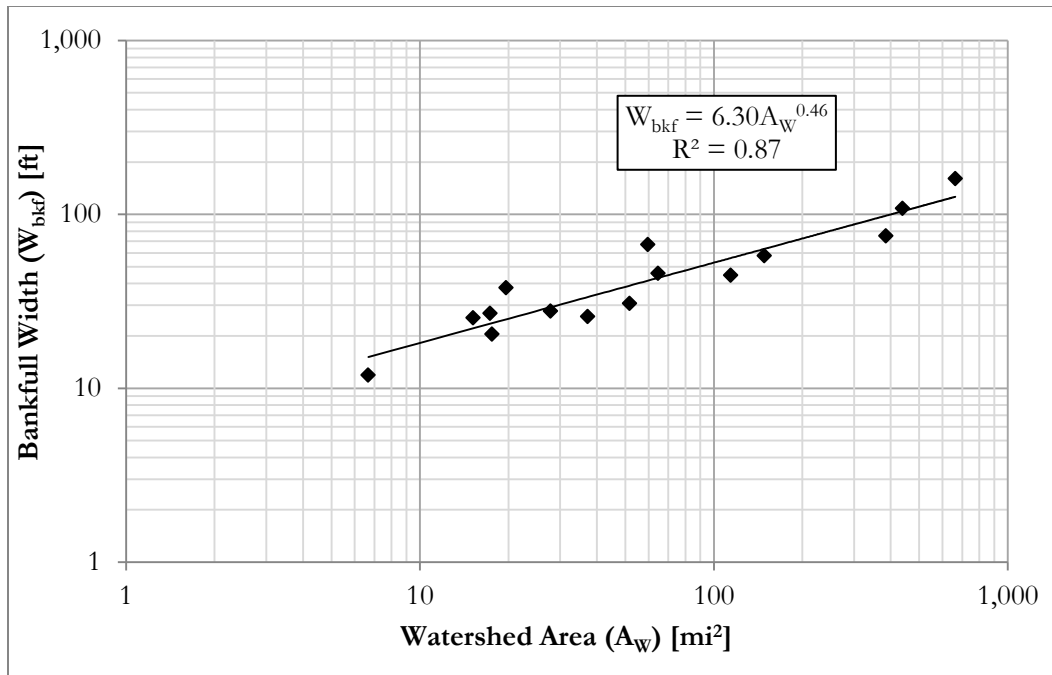


Figure 4.17 – Regional curve relating bankfull width to watershed area (Equation 4.1). The solid line represents the proposed regional curve.

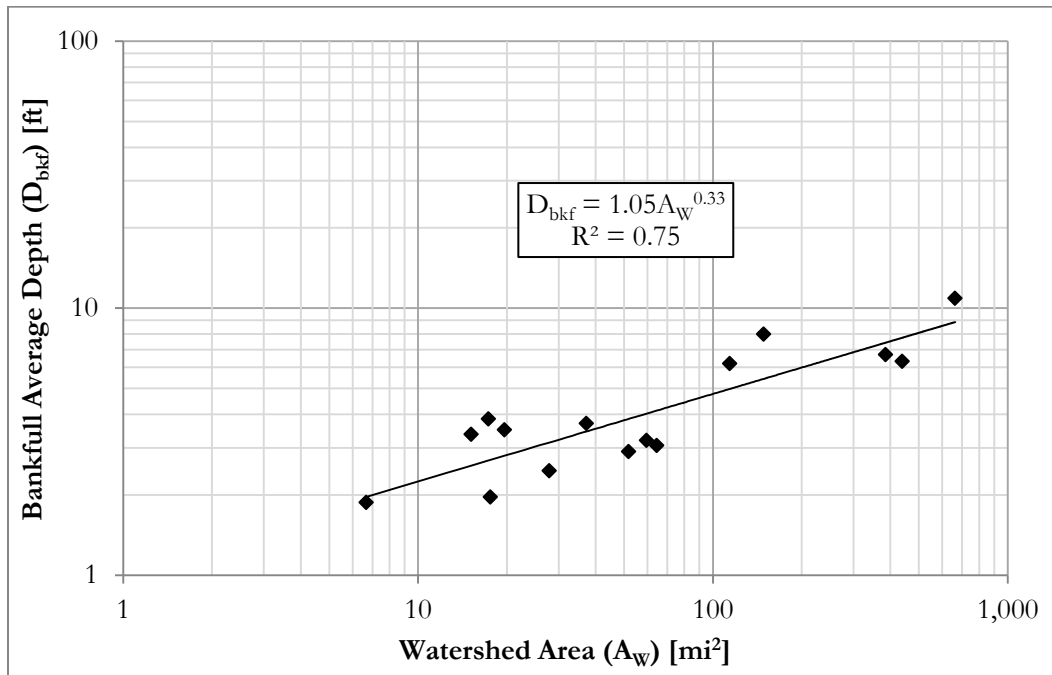


Figure 4.18 – Regional curve relating bankfull width to watershed area (Equation 4.2). The solid line represents the proposed regional curve.

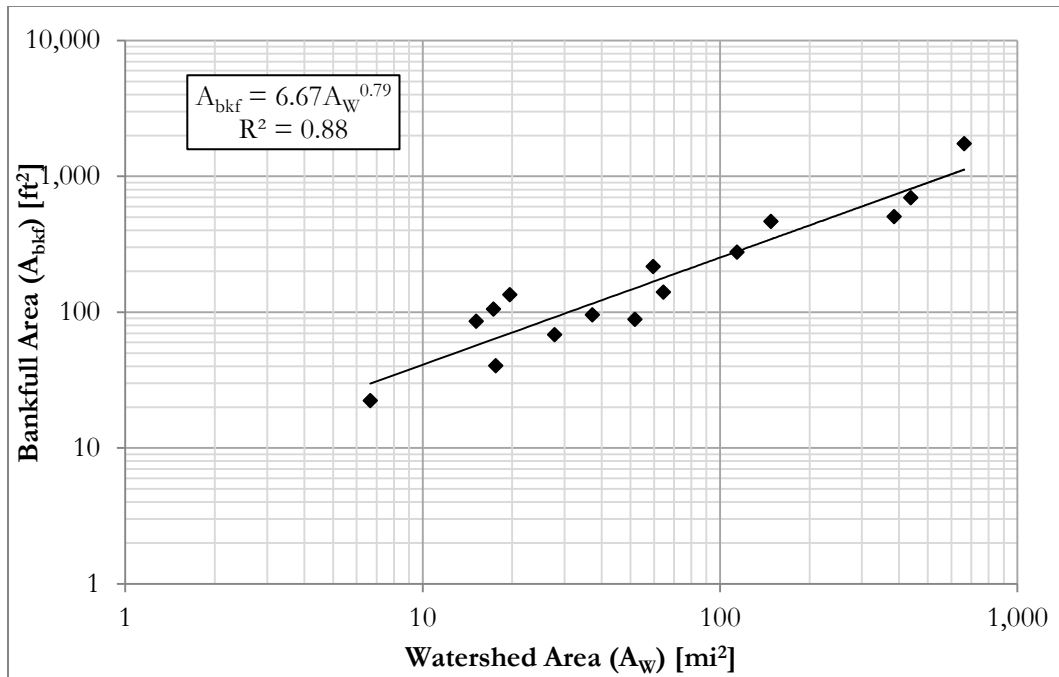


Figure 4.19 – Regional curve relating bankfull area to watershed area (Equation 4.3). The solid line represents the proposed regional curve.

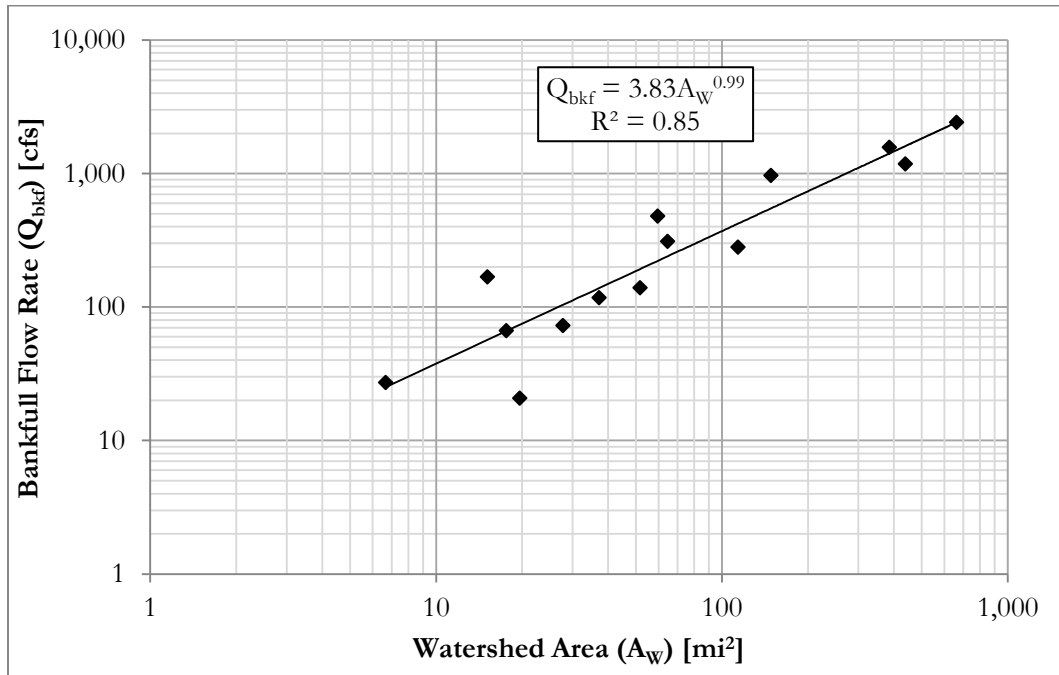


Figure 4.20 – Regional curve relating bankfull flow rate to watershed area (Equation 4.4). The solid line represents the proposed regional curve.

4.5.3 Channel Morphological Metrics

Correlations were determined between watershed area, bankfull geometry (width, depth, cross sectional area, and flow rate), measures of bed substrate (D_{16} , D_{50} , and D_{84}), slope, and indices of stream function (recall: QHEI, RBI, bankfull occurrences per year, bedload (tons/sq. mi/yr), and TVI). Other than the hydraulic geometry relations mentioned previously, one correlation was found between log transformed D_{50} and square root transformed RBI values ($R = 0.76$, $p=0.002$). Further investigation through a regression analysis yielded a significant linear regression of $R^2 = 0.61$ ($p=0.002$) between the transformed datasets (see Figure 4.21).

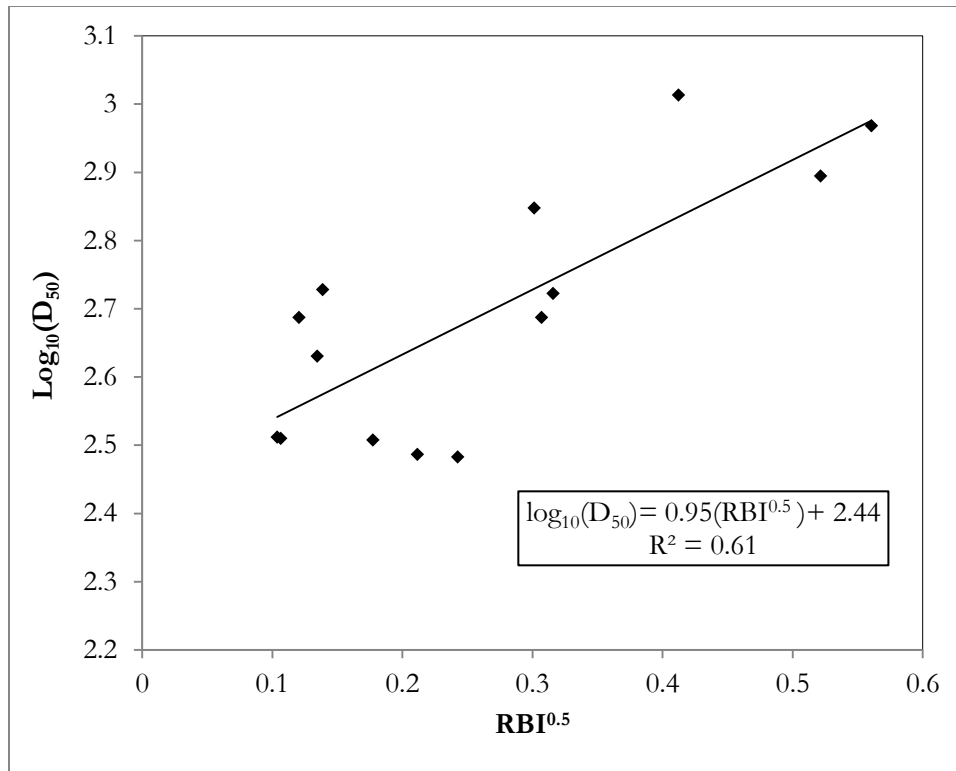


Figure 4.21 – Linearized relationship between RBI and D_{50} (D_{50} is measured in μm).

Table 4.8 – Significant correlations ($p < 0.05$) between physical stream components and indices of stream function. Correlations above the 0.7 threshold are bolded and underlined.

	QHEI	RBI	Bkf/yr	H	BL _{yr} /A _w	TVI
A _w	-0.35	0.12	-0.14	-0.02	-0.06	-0.44
S	<u>0.69</u>	-0.05	-0.21	0.48	0.54	0.31
W _{bkf}	<u>-0.69</u>	0.19	-0.27	0.08	-0.12	-0.47
D _{bkf}	<u>-0.64</u>	0.18	-0.18	-0.04	-0.42	-0.34
A _{bkf}	<u>-0.69</u>	0.19	-0.25	0.03	-0.26	-0.44
Q _{bkf}	-0.39	0.38	-0.33	0.35	0.07	<u>-0.60</u>
D ₁₆	0.30	0.59	-0.10	0.54	0.06	-0.20
D ₅₀	-0.24	<u>0.76</u>	-0.39	<u>0.61</u>	-0.24	-0.25
D ₈₄	0.15	0.36	-0.57	0.43	0.19	0.26
n	0.07	-0.43	-0.22	-0.18	-0.02	0.47

Other correlations existed between three of the bankfull geometry components relationships with QHEI. Bankfull width, depth, and cross sectional area correlated with QHEI ($R = -0.69$, -0.64 , and -0.69 ; respectively, with p -values of 0.016, 0.014, and 0.01). This suggests that as stream dimensions increase, the QHEI scores tend to decrease. Also, slope was found to correlate to QHEI ($R = 0.69$, $p = 0.003$). The next notable correlation was the negative correlation between bankfull flow rate and TVI ($R = -0.60$, $p = 0.087$). This suggests that larger rivers tend to have lower temperature variation. This could like be due to differences in groundwater inputs or depth. A similar finding is outlined in Poole and Berman (2001). Hammer number also was found to positively correlate with D_{50} ($R = 0.61$), meaning that larger bankfull flow rates relative to watershed area tended to result in coarser-than normal bed material.

4.5.4 Bedload and Stream Stability

Bed load (tons/sq. mi/yr), when compared to all other independent values (land cover indices, hydraulic geometry, soils, etc.), yielded no correlations greater than $R = 0.6$ (as can be referenced in Table 4.8 and Table 4.9). However, bedload was found to be correlated to another component of

stream flow function, QHEI ($R=0.76$ $p=0.002$), with the regression with annual bedload explaining 57% of the variation of QHEI ($R^2=0.57$, $p=0.002$) (see Figure 4.22).

Table 4.10 – Significant correlations between the various indices of stream function. Correlations above the 0.7 threshold are bolded and underlined.

	QHEI	RBI	H	Bkf/yr	$BL\bar{V}_{yr}/A_w$	TVI
QHEI	-					
RBI	-0.17	-				
H	0.27	<u>0.68</u>	-			
Bkf/yr	0.04	-0.38	-0.52	-		
$BL\bar{V}_{yr}/A_w$	<u>0.76</u>	-0.12	0.24	-0.23	-	
TVI	0.30	-0.65	-0.38	0.11	-0.10	-

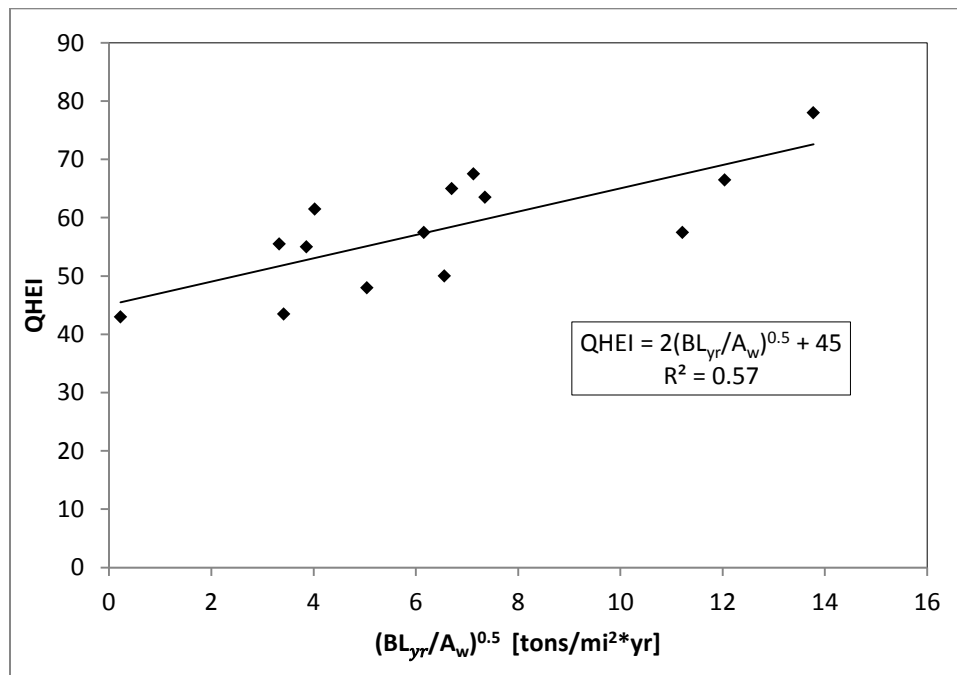


Figure 4.22 – Regression graph for QHEI graphed against BL_{yr}/A_w and trend line using all study sites.

4.5.5 Other Correlations

The comparison of components of stream flow function against themselves was done to not only ensure that there were no hidden correlations (*lurking variables*), but to investigate the inter-correlation between stream flow metrics. There were two correlations that surfaced. The first was between \log_{10} transformed values of Hammer number and square root transforms of RBI ($R=0.68$, $p=0.007$). The other notable correlation was between RBI and TVI ($R=-0.65$, $p=0.060$). This correlation suggests as flashiness (RBI) increases, temperature variation (TVI) decreases. These findings were summarized previously in Table 4.10.

5 DISCUSSION

5.1 THE INFLUENCE OF LANDSCAPE ON STREAM FLOW FUNCTION

The raw results of landscape, in terms of percentages of agriculture, forest, and wetlands as well as metrics of percent impervious, LDI, and average CN did not vary much suggesting that the investigated watersheds had similar hydrologic character. Some trends included the high coverage (>50%) of wetlands within much of the riparian buffer, the relatively high average CNs found in rural areas (like Jeffries Creek (DNR), CN=75), and the prevalence of agricultural land cover within some of the largest watersheds (namely, Thompson Creek and Lynches River with 40 and 50 percent agriculture, respectively). In this study, landscape indices that were used all characterize the impacts of urbanization on the landscape. These indices included LDI, TIA, and % Developed. Each was investigated for the possibility of application across the study region. The area of the state that the South Carolina Pee Dee Project (SCPDP) sites are located is largely rural, dominated by forest, field, wetland, and agriculture land use, and therefore low percentages of impervious landscape, low LDI's, and relatively low CN values. Ideally, landscape indices would be able to incorporate more land cover classes than solely development classes, as rural South Carolina is not typically characterized by urbanized landscapes. The method of investigation was similar to previous studies that also examined the effect of landscapes and land cover classes in besides urbanization (Poff et al., 2006; Wood-Smith and Buffington, 1996). This presents a relatively unique opportunity to determine causes for change in bankfull occurrence, bed load, Richards-Baker Flashiness, Hammer number, QHEI, as well as many other components of stream flow function, beyond the effects urbanization. However, urbanization was still investigated in the lower Pee Dee Region, much as it had been in other studies (e.g. Booth et al., 2004; Changnon and Demissie, 1996; Swank et al., 1988).

5.1.1 The Significant Contribution of Wetlands

Similar to what Sponseller et al. (2001) determined, physical components of the stream tended to be affected by land cover within the riparian corridor. There are many other studies that exist that attempt to quantify the spatial relation of land cover to the stream (Gergel et al, 2002; Richards et al., 1996; Omernick et al, 1981.). The results from this study paralleled those of Sponseller et al. (2001), where most variation in stream behavior could be most related to the riparian corridor. The relations that exist within these scales are primarily related to one land use: wetlands.

Influence of Wetlands on Watershed Outflows

In the National Land Cover Dataset, wetlands are classified as *Woody Wetlands* or *Emergent Herbaceous Wetlands*. In this study, these land covers were combined into a single *wetland* land cover. In the Lower Pee Dee watershed emergent herbaceous wetlands are consistently between 1-and-6% of the total wetland coverage. Therefore, many of the correlations discussed between wetlands and other stream flow metrics in this document are more of a function of the presence of woody wetlands on the landscape than emergent herbaceous wetlands.

Wetland percentages at the entire buffer scale tended to result in lower RBI values, essentially moderating the extreme flows of a stream. This is due to the assimilative capacities of wetland systems and their inherent ability to attenuate flows that pass through them (Hillman, 1998). The data show that as the percentage of wetlands within the stream riparian buffer increase, there is an apparent decrease in RBI. This correlation was found at two scales; the *entire riparian buffer* and *catchment* scales. However, the correlation at the catchment scale is an effect of the much stronger correlation at the *entire riparian buffer* scale ($R^2=0.69$, $p<0.001$ and $R^2=0.74$, $p<0.001$; respectively). Nonetheless, this result potentially holds implications in regulation of riparian area of streams throughout the State, especially in regards to the potential protection of wetland riparian areas and those co-occurring plant and animal species.

The correlation between wetland percentage within the entire buffer and Hammer number could be a function of two separate mechanisms of wetland hydrology. The first is the tendency for wetlands to attenuate peak flows (flood waves, storm surges, etc.) and therefore decrease the hydrograph peak and extend its duration (Gedan et al., 2010; Hillman, 1998; Woo and Waddington, 1990). This dampening effect results in lowered flow rates and a lower defining bankfull flow rate. For the second mechanism, a native ecosystem engineer, the beaver, may be a source of causation of some wetlands and their subsequent effect on stream systems. In particular, wetlands created by beavers have the ability to attenuate peak flows (Woo and Waddington; 1990) and essentially act as a semi-permanent flow regulator (such as a weir). In a historical context, beavers were significant contributors to the landscape, with populations as high as 400 million (they are now estimated at 6-12 million) (Naiman, 1988). In fact, beavers often contribute “to the formation of extensive wetland habitat” (Wright et al., 2002). Beavers have already affected three of the original 16 SCPDP sites (Jeffries Creek DNR, Huckleberry Branch, and Little Fork Creek), and as populations increase, this will become a more frequent occurrence. Such activity could be considered as a possible component of the revitalization and protection of the river system, or if nothing else, a tool used to provide a buffer against flashy flows. Also, a weaker correlation was found between Hammer Number and percentage wetland within the catchment. However, this is due to the much stronger correlation found at the entire riparian buffer scale.

Temperature variation increase with wetland prevalence

A higher amount of wetlands within the entire riparian buffer was also found to be positively correlated to an increase in the Temperature Variation Index (TVI). In other words, temperature variation increased as the wetland prevalence in the riparian buffer increased. This was due to the prolonged period of atmospheric exposure of water within the wetland as well as increased albedo caused by the highly organic contents of a wetland, which are typically dark. Another possible

explanation is that in the studied area of the Pee Dee watershed, there are two distinct flow regimes: winter (Nov-March) and summer (May-Oct) flows. Winter flow rates are less impacted by evapotranspiration tend to have higher, flashier flow rates, higher base flows, and may have greater groundwater (Wittenberg, 2003) input during this period. Summer flow rates are greatly affected by high summer evapotranspiration rates and tend to of lower magnitude, with lower base flow contributions, and lower flashiness values. By classifying the temperature data as summer or winter values, it was apparent that stream temperatures in the winter varied considerably more than summer (TVI_{WINTER} ranged from 0.491 to 1.114, while TVI_{SUMMER} ranged from 0.370 to 0.728). TVI_{SUMMER} values were no longer as correlated to wetlands in the 1000 m buffer ($R=0.69$ and $p\text{-value}=0.025$), when compared to the initial $R=0.72$. TVI_{WINTER} values were more significantly correlated ($R=0.73$ and $p\text{-value}=0.016$). Although temperature variation may a limited or negligible effect on fluvial processes of a stream, relationships between temperature and chemical/biological properties are more profound (Kratzer and Batzer, 2007; Bachand and Horne, 2000; Nakano et al., 2000; Marshall and Elliot, 1998). Highly variable temperatures in the winter may be component of wetlands ability to naturally regulated dampen nutrient loads, an attribute of wetlands that is well-documented in literature (Fisher and Acreman, 2004; Jing et al., 2001; Nichols, 1983). The positive correlation between temperature variation and watershed prevalence will provide insight into chemical and biological dynamics that must be assessed before a method of determining Minimum Allowable Flows for the Pee Dee Watershed can be established.

5.1.2 Other Land Cover Classes as Drivers of Stream Flow Function

CN and the prediction of stream flow behavior

Similar to what other sources found (Pizutto et al., 2000; Hammer, 1972), CN in the 1000 m and 2000 m riparian buffer classes are positively correlated with Hammer Number. In other words with bankfull flow rates typically increase with the modification of the natural landscape. Recall that Hammer number is simply bankfull flow rate (Q_{bkt}) divided by watershed area (A_w). As bankfull flow rates increase with urbanizing landscapes, the Hammer number will also consequently increase. The limitation of a correlation between Hammer number and CN to only the 1000 m and 2000 m riparian scales are caused by factors that influence by distance to the sampling point such as time of concentration, propagation of flood waves, etc. (Lai et al., 2000). This limited-scale correlation between Hammer number and CN may also indicate that stream flow coming from reaches further upstream are perhaps to be more affected by other components that cannot be classified using a simple averaged CN, such as upstream impoundments, changes in channel morphology, or the presence of other land cover classes (e.g. wetlands, forests, etc.).

The decrease in bankfull occurrences with the increasing CN

Higher curve numbers, typically associated with agriculture, urbanization or development, are commonly associated with higher peak flows due to more surface runoff and less infiltration (Pizzuto et al., 2000). These same flows are also associated with higher bankfull recurrences than those 'undisturbed' or natural streams. Bankfull occurrences in the SCPDP did not appear to conform to those in published studies, often occurring more often than those reported in literature; typical values for bankfull occurrence in natural rivers fall between 1 and 2 occurrences per year (Castro and Jackson, 2001; Moscrip and Montgomery, 1997; Chang, 1988; Klein, 1979; Dunne and Leopold, 1978; Leopold, 1968). Curve Number at both the entire riparian buffer scale and entire catchment

scale yielded a negative correlation with the number of bankfull occurrences per year. This negative correlation is contrary to published studies where it was determined that as development increased (and therefore CN increase), larger flows tended to occur more frequently (Booth and Jackson, 1997; Moscrip and Montgomery, 1997). Perhaps these results that show a decreasing bankfull occurrence with increasing CN is more of a function of the relative age of the landscape, as most of the development in the area is older than the 4 -year threshold that Hammer established in 1972. Hammer (1972) found that impervious area less than 4 years old tended to have a larger effect on stream morphology than impervious area greater than 4 years old. Therefore, the channel areas in this study have already adapted their cross sectional area to compensate for changes in hydrology, having a subsequent effect on bankfull recurrence.

By comparing some the cross sections of the monitored watershed in the Pee Dee to the Channel Evolution Process described by Schumm et al. (1981), the trend of decreasing bankfull flow recurrence is a logical progression. This is because the streams in question (especially Thompson Creek and Little Fork Creek) tend to be in Stage II or III of the Channel Evolution Process, a scoured state. As the bed scours or incises, bankfull flow rates that once reached the floodplain are effectively cut off due to the lowering of stream bed elevation. The decrease in streambed level may have left misleading visual evidence of bankfull elevation, lead to the incorrect estimation of a bankfull elevation and therefore, a bankfull flow rate.

Booth and Jackson (1997) used a 10-year recurrence interval flow rate rather than bankfull elevation (a measurement that assumes the stream is in dynamic equilibrium) to explain the discrepancy between age of development and CN. When a stream is incising, previous bankfull elevations are no longer valid because the determination of bankfull elevation becomes more vague, as signs of the bank begin to conflict with each other. The substantial increase in bankfull “fuzziness” (Johnson and Heil, 1996) may invalidate any use of a bankfull elevation in these streams, and a method like Booth

and Jackson's (1997) 10-year recurrence interval would be a more appropriate measure for a degrading stream system. Of course this implies several decades of measured stream flow at that site.

The increase in RBI with the increase of forests in riparian buffers

While the positive correlation found between the percent forested land at the entire riparian buffer scale and RBI could be more of a function of the loss of wetlands than the presence of forest, Baker et al. (2004) found that increases in flashiness could be attributed to land cover classes other than developed, namely agricultural and forested. This phenomenon may be an inherent weakness of the use of the National Land Cover Dataset (NLCD), which uses reflectance to characterize land cover (US EPA, 2006), and does not indicate actual *land use*. As a result, land uses like silviculture are often neglected from such analyses. This is significant because silvicultural lands are often drained with ditches, which short-circuit the hydrology of the system and result in higher peaks, lower base flows, and overall flashier flows in the stream systems on silvicultural land. These are alluded to in literature in the study of both agricultural and silvicultural lands (Schoonover et al., 2006; Baker et al., 2004; Xu et al., 2001). Increases in RBI may also be influenced by more than land use, and could be functions of ecoregion (Baker et al., 2004), soils (Fongers et al., 2007), and imperviousness (Fongers et al., 2007; Booth and Jackson, 1997).

5.3 FLUVIAL GEOMORPHOLOGY AND STREAM FLOW FUNCTION

5.3.1 Manning's n and one dimensional flow

All flows were characterized using the one-dimensional Manning's Equation (Gauckler, 1867). The resulting flow resistance, which in reality varies as function of three dimensional processes (such as turbulence, bed form, channel sinuosity, flow depth, etc.), is represented in this study using a single-dimensional equation. Manning's resistance uses a single term (n) to approximate a three-dimensional

and highly variable phenomenon that is flow resistance. Perhaps this is why the n -value ranged so greatly in this survey (0.038 to 0.107). These roughness values do not fall in the typical ranges of channel n -values, reported as being between 0.02-0.1 for sand-cobble-bed streams (Limerinos, 1970). However, published studies of research on sand bed streams have reported n -values ranging from 0.023-0.220 (Jayakaran et al., 2005; Wilson and Horritt, 2002; Dudley et al., 1998; Marcus et al., 1992; Chow, 1959). As the n -values were back-calculated (as in Chow, 1959) and not derived from empirical or qualitative surveys (Marcus et. al., 1992; Limerinos, 1970), n -values in this study (and Chow, 1959) seem uncharacteristically high, with the highest values tending to fall into the deep and highly debris-ridden reaches (as tested in Dudley et al., 1998) with sluggish, deep pools. Sluggish, deep streams are common in the Pee Dee Basin, a detail that became evident upon the investigation of the Manning's roughness coefficients that were calculated. As apparent by the considerable ranges of n -value estimates that exist for streams (0.05-0.22 in Wilson and Horritt, 2002; 0.02-0.1 in Limerinos, 1970; 0.02-0.16 in Chow, 1959), there are inherent shortcomings in the simplification of three-dimensional flow to one-dimensional flow. However, due to the intrinsic complexities of measuring 2-and-3-dimensional flows, the shortcomings of one-dimensional flow simplification are justified for this study.

5.3.2 Hydraulic Geometry and Regional Curves

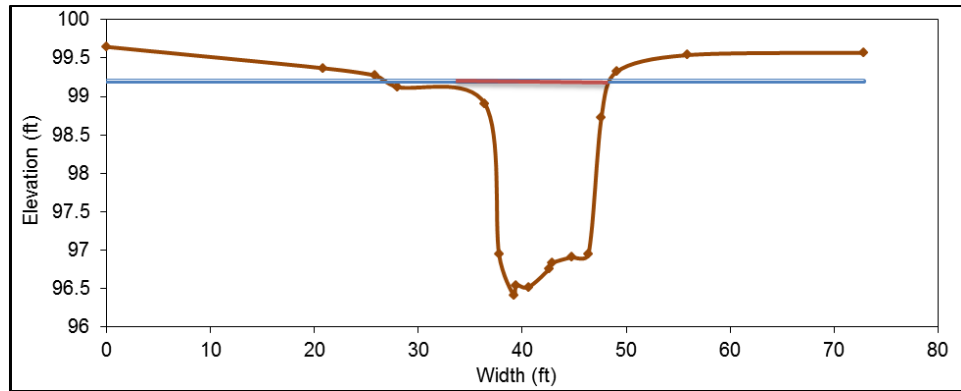
Regional curves derived from relationships between hydraulic geometry and catchment area were developed within the SCPDP. Initially reported by Dunne and Leopold, 1978; and later modified by Leopold, 1994, regional curves have since been developed across the country for various topographic regions. These include studies in the Pacific NW (Castro and Jackson, 2001), Pennsylvania and Maryland (Cinotto, 2003), northern Florida (Metcalf et al., 2009), Midwestern agricultural streams (Jayakaran et al., 2005) and the piedmont (Doll et al., 2002) and coastal plains (Sweet and Geratz, 2003) regions of North Carolina. Regional curves derived in the SCPDP region had coefficients of

determination that fell within the range reported in literature, with reported curves having coefficients of determinations as low as 0.54 (Castro and Jackson, 2001) to as high as 0.99 (Metcalf et al., 2009); the highest coefficients of determination typically being those that compared bankfull area and flow rate to watershed area (Sweet and Geratz, 2003; Doll et al., 2002), and the lowest consistently being average depth (Metcalf et al., 2009; Cinotto, 2003; Sweet and Geratz, 2003; Doll et al., 2002; Castro and Jackson, 2001;).

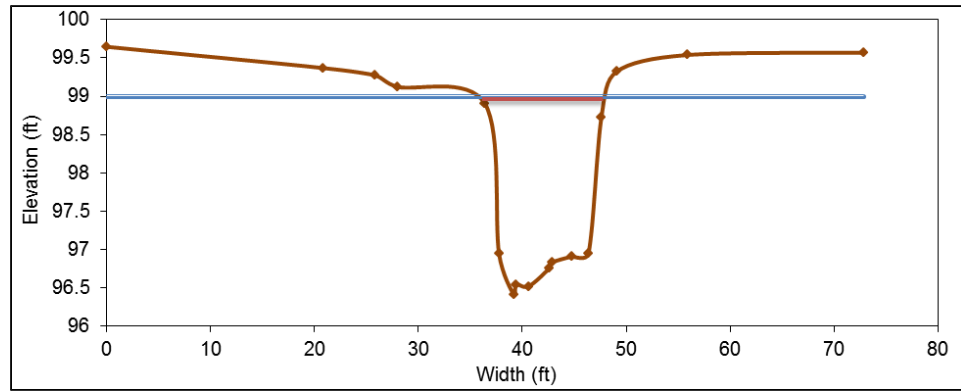
Implications of bankfull elevation discrepancy

The lower R^2 values of width and depth in other studies are likely due to the vulnerability of measurements of width and depth to small variations in the determined bankfull depth. This, coupled with bankfull elevation being a “fuzzy” number, whose variation can be attributed to the presence of many possible conflicting indicators (Johnson and Heil, 1996), sets the stage for rather large variations in hydraulic geometry. In both average bankfull depth (D_{bkf}) and bankfull width (W_{bkf}), these variations seem to be large, while leaving bankfull area (A_{bkf}) and flow rate (Q_{bkf}) relatively unchanged. This susceptibility to bankfull estimation errors is quite possibly the cause for bankfull depth in the Pee Dee region yielding the lowest R^2 value. This concept of bankfull vulnerability is perhaps best conceptualized in Figure 5.1a-b.

In Figure 5.1a, the bankfull elevation was determined to be 99.2ft. This bankfull elevation resulted in a cross section with an average depth of 1.11ft, width of 19.0ft, and area of 21.1ft². In Figure 5.1b, bankfull elevation was determined to be only slightly lower, at an elevation of 99ft (a difference of 2.4 inches). The average bankfull depth changed by 27% to 1.41ft while the width changed 33% to 12.6ft. However, upon removing the small, localized effects of floodplain terrain and focusing on the actual channel bed, the red line can be redrawn to prevent overestimating width and the subsequent underestimation of average depth.



(a)



(b)

Figure 5.1 – Demonstration of the effect of slight changes of bankfull elevation on (a) D_{bkf} and (b) W_{bkf} . The brown line is the cross section of a stream, the blue is the water level, and the red is the proposed measurement limit for bankfull depth and width.

Following this procedure (of *effective width*¹⁵), Figure 5.1a yields a width of 14.0ft and depth of 1.8ft while Figure 5.1b yields a width of 11.5ft and depth of 1.9ft (only 18% and 8% changes, respectively). The widespread use of effective width would result in less variable determinations of bankfull values.

¹⁵ *Effective Width* is concept that is incorporated into the Reference Reach Spreadsheet (Mecklenburg and Ward, 2009) and utilized in the SCPDP.

Atlantic Coastal Plain Regional Curves

The comparison of SCPDP regional curves to two other eastern coastal plain studies (Metcalf et al., 2009; Sweet and Geratz, 2003) show that hydraulic geometry of geographically proximal and topographically comparable regions are similar. The regression line fitted to a plot of D_{bkf} and W_{bkf} against drainage area tended to have significantly different slopes between regions and/or studies (Figure 5.2).

Following the generic power-form equation of Leopold (1994) for regional curves, the regional curve for the bankfull width of the SCPDP sites had a higher exponent (0.46) and lower constant (6.30) than those found in literature for the same region. This range of exponents and constants in similar regions varied from 0.28-0.39 and 9.2-10.4, respectively (Metcalf et al., 2009; Sweet and Geratz, 2003). However, the range of predictions seemed to be maintained throughout the region, having no greater than a 10ft difference in bankfull width between curves with the exception of the North Florida/Georgia Coastal Plain (Metcalf et al., 2009).

Meanwhile, the regional curve for mean bankfull depth (D_{bkf}) for SCPDP sites had an exponent of 0.34 and constant of 0.998; both within the range of the values found in literature for southeastern coastal plains. In the Southeastern Coastal Plains, the values of constant and exponents range from 0.25-0.43 and 0.67-1.64, respectively (Metcalf et al., 2009; Sweet and Geratz, 2003). Predictions of D_{bkf} by each of these southeastern coastal stream regional curves seemed to be the most variable in watersheds smaller than 10 square miles and seemed to converge near watersheds of 100 square miles.

The regional curves of bankfull cross sectional area (A_{bkf}) against drainage area (A_c) tended to have the most similar slopes and constants within the Atlantic region with the exponents ranging from 0.64-0.77 and constants ranging from 7.3 to 17.3 (Metcalf et al., 2009; Sweet and Geratz, 2003; and the SCPDP). Among the different hydraulic geometries generated for SCPDP sites, the regional curve

of bankfull discharge seems to be the most dissimilar when compared to the literature of the region (Metcalf et al., 2009; Sweet and Geratz, 2003). Broken down, the SCPDP region had the most dissimilar exponent for bankfull flow rate (0.99) when compared to other regional curves in the area (see Figure 5.2d), which had exponents that ranged from 0.71-0.77. However, the Northern Florida/Alabama Coastal plain had the most dissimilar constant for the regional curve (27.7) when compared to 3.59-8.79 range of the regional curves summarized in Figure 5.2d while remaining essentially parallel to the NC Coastal Plain and the Northern Florida/Georgia Coastal Plain. Metcalf et al. (2009) states that this variation was due to differences in rainfall pattern between the regions. Despite these relatively small discrepancies, each of the regional curves outlined in the SCPDP, Metcalf et al. (2009), and Sweet and Geratz (2003), remain generally similar to each other.

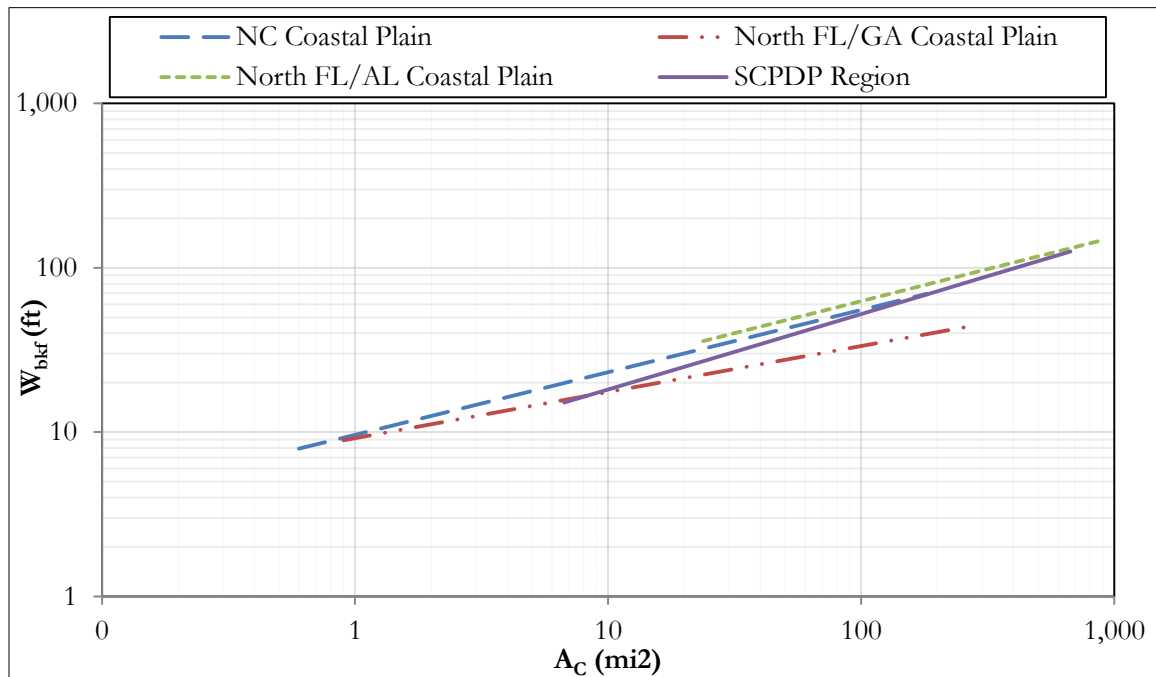


Figure 5.2a – Regional Curves of Catchment Area vs. Bankfull Width by various studies from the Southeastern Atlantic coastal plain region (SCPDP; Metcalf et al., 2009; Sweet and Geratz, 2003). These curves are strictly interpolated, with no line extending beyond the dataset they were derived from.

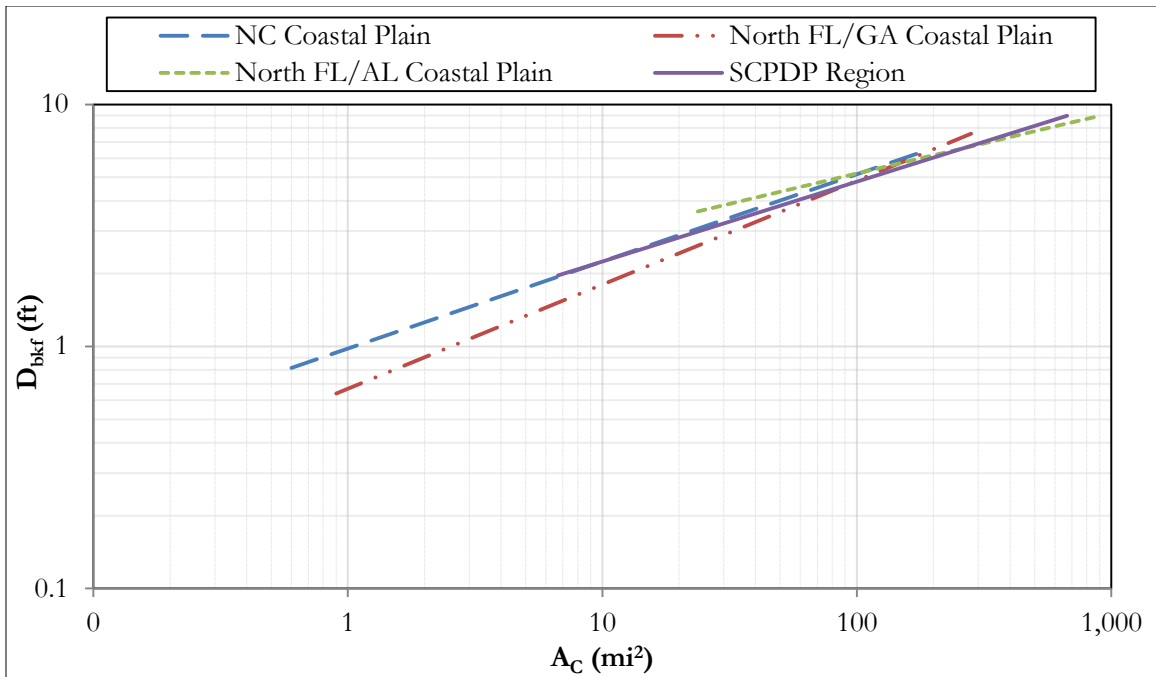


Figure 5.2b – Regional Curves of Catchment Area vs. Bankfull Depth by various studies from the Southeastern Atlantic coastal plain region (SCPDP; Metcalf et al., 2009; Sweet and Geratz, 2003). These curves are strictly interpolated, with no line extending beyond the dataset they were derived from.

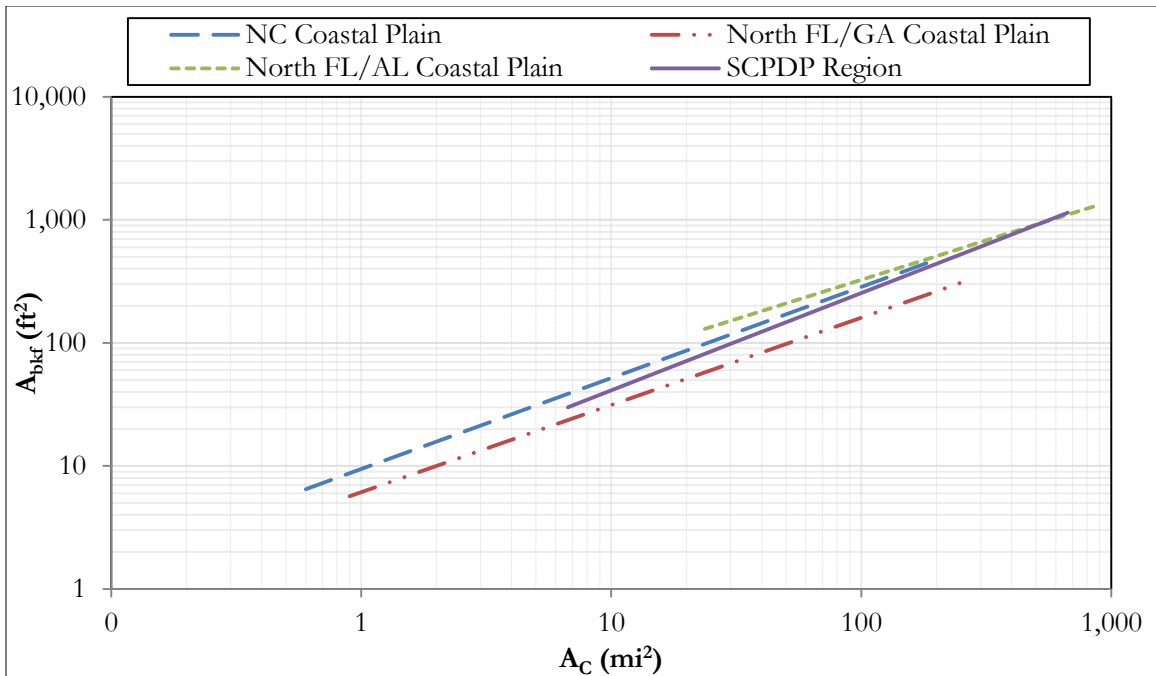


Figure 5.2c – Regional Curves of Catchment Area vs. Bankfull Cross Sectional Area by various studies from the Southeastern Atlantic coastal plain region (SCPDP; Metcalf et al., 2009; Sweet and Geratz, 2003). These curves are strictly interpolated, with no line extending beyond the dataset they were derived from.

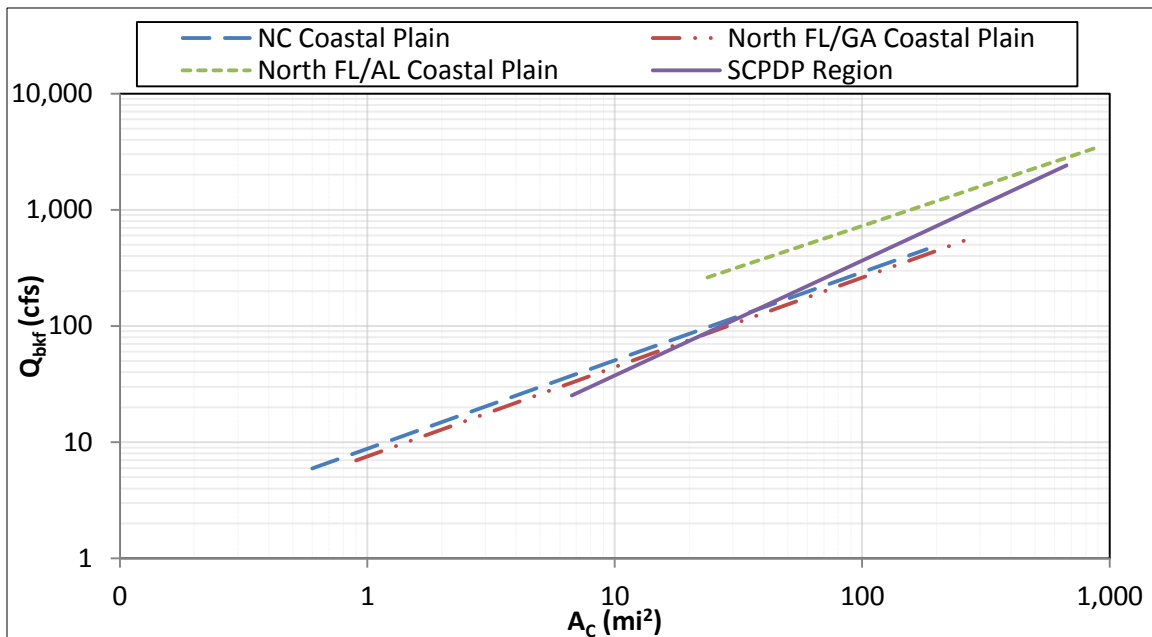


Figure 5.2d – Regional Curves of Catchment Area vs. Bankfull Discharge by various studies from the Southeastern Atlantic coastal plain region (SCPDP; Metcalf et al., 2009; Sweet and Geratz, 2003). These curves are strictly interpolated, with no line extending beyond the dataset they were derived from.

Of course, all regional curves could be compared from the many studies that have been conducted (Metcalf et al., 2009; Cinotto, 2003; Sweet and Geratz, 2003; Doll et al., 2002; Castro and Jackson, 2001), but different topographies, ecoregions, etc. produce vastly different curves, highlighting the need to produce geographically specific regional curves. A comparison of multiple regional curves is presented in Figure 5.3, highlighting the importance of topography on stream dimensions.

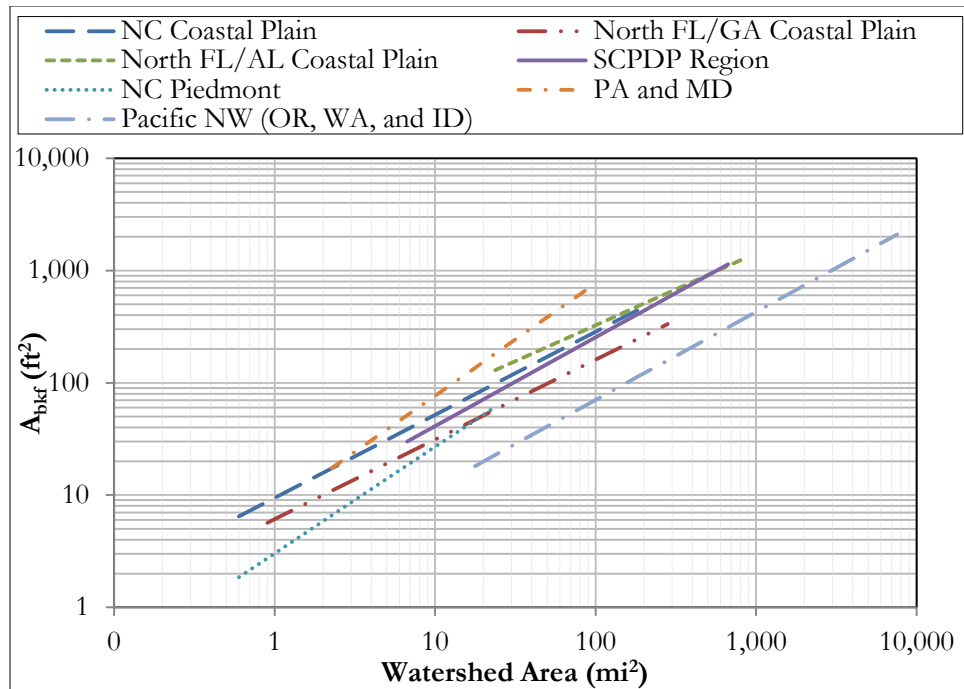


Figure 5.3 – Comparison of 7 regional curves from across the country. As before, no regional curve extends beyond the bounds of its dataset.

Many other curves have been derived for other areas across the country and the world. For further reference, many other regional curves reported between 1960 and 2001 are summarized in Table 1 of Jayakaran et al. (2005).

Hydraulic geometries and QHEI

The negative correlations between the hydraulic geometry measurements of width, depth, and cross sectional area and QHEI are due to several factors that make QHEI inherently bias towards smaller, headwater streams. The first is the known phenomena of the downstream fining (Dade and Friend, 1998). The QHEI gives higher scores for larger substrate, and therefore, the score will naturally drop as you follow a river downstream. The second is the perception of *Instream Cover*, a heading on the QHEI form. As a stream system grows larger, the perception of the amount of cover naturally decreases due to the streams size relative to the material within it, as well as the instream cover hidden below the water surface. The last possible reason for the decrease in QHEI as stream size

increases could be the divergence from the pool-riffle systems more typical in smaller streams and towards more of a plane-bed stream at the larger sites within the SCPDP (these classifications can be found in Montgomery and Buffington, 1997). These same concepts apply to the positive correlation between slope and QHEI. Results from the lower Pee Dee Basin indicate that as slope increases, bed substrate size increases, stream size generally decreased, and the apparent instream cover increases.

These correlations are an inherent shortfall of using such qualitative assessments across many different types of streams as well as highlighting the possible (and probable) shortfall of any qualitative survey, resulting from perception biases. However, surveys such as the QHEI are valuable tools in the initial characterization of a stream, but rather a useful and effective supplement (Rankin, 1989).

5.4 SOURCES OF VARIATION IN BED MATERIAL

5.4.1 Downstream Fining

Whether a stream is impounded or not has important ramifications on the availability of sediment for transport within the stream system. Impoundments have been shown to reduce the transport of sediment to downstream reaches by as much as 99% (Brandt, 2000). Downstream of the impoundment the stream is forced to compensate for the paucity of sediment available for transport. Bed material now unavailable from the reach upstream of the impoundment, tends to be sourced from the stream bed itself resulting in a coarsening of the bed (Brandt, 2000; Chein, 1985). In the Pee Dee basin, no correlations were found between bed material and slope, watershed area, or other flow characteristics. However, downstream fining did occur within some streams that were sampled within the Pee Dee River, as was predicted based on previous findings in other river systems (Paola and Seal, 1995; Dade and Friend, 1998).

Of the 16 sites, 15 were within the same stream network of at least one other site, in a total of 5 groups. These will be labeled as Groups 1 through 5. Each group can be found in Figure 5.4, which is a conceptualization of the stream networks that connect the 16 sites measured in this study.

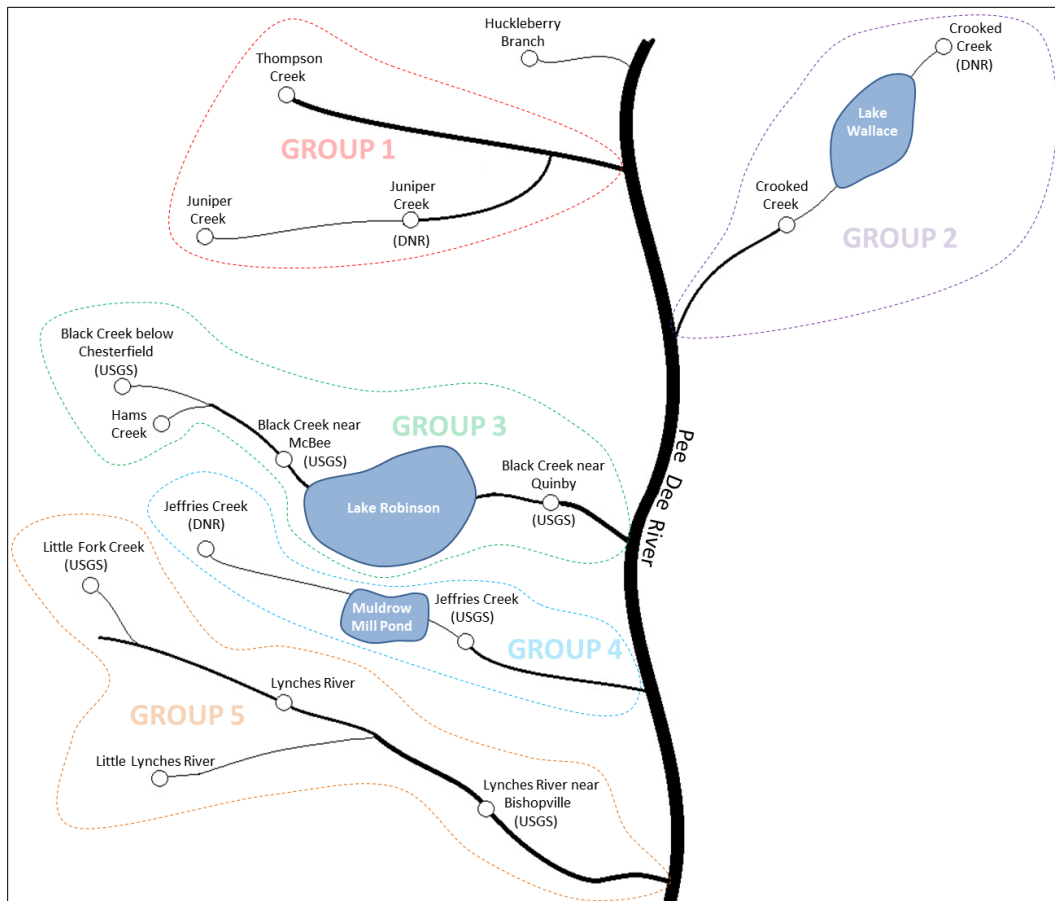


Figure 5.4 – Selected stream networks within the Pee Dee that were sampled as part of the Pee Dee Project. Each stream network is labeled as one of five groups with thicker lines within the network representing larger streams.

Of the 5 groups, there were 2 were not impounded (having no man-made lakes or reservoirs between the individual sites in each respective group). In the groups that were not impounded, downstream fining did occur (see Figure 5.5).

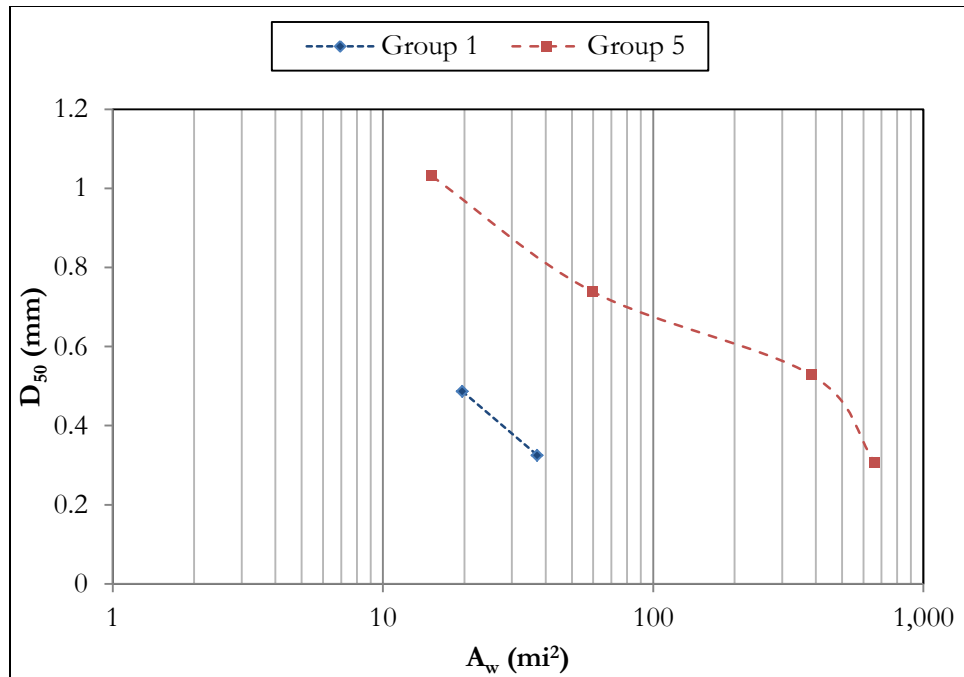


Figure 5.5 – Illustration of downstream fining trend in unimpeded stream systems in the Pee Dee.

More investigation is required to corroborate these results, as there are currently not enough sites in any one unimpounded group to make any conclusive statements. Within the Pee Dee watershed (see Figure 5.4) reservoirs exist between Black Creek at Mcbee and Black Creek at Quinby (Lake Robinson, approximately 18.1 mi²), Crooked Creek (DNR) and Crooked Creek (Lake Wallace, approximately 4.3 mi²), and Jeffries Creek (DNR) and Jeffries Creek (USGS) (Muldraw Mill Pond, approximately 0.05 mi² within 3 miles of the stream). At each of these sites, coarsening occurred between the site in question and the site upstream.

5.4.2 Stream Flow and Sediment Size

Richards-Baker Flashiness and the Coarsening of Characteristic Sediment

When looking outside of simple relationships between fluvial geomorphology and other measurements or metrics, a significant linear relationship was found between median grain size (D_{50})

and RBI ($R^2 = 0.61$, $p=0.002$). Since RBI is a sum of the daily flow rate variations, higher RBI numbers indicate that the stream is subject to higher peak flows and/or higher frequencies of occurrence of larger flow rates relative to its average flow rate (Baker et al., 2004; Poff et al., 1997). Also associated with flashy flow are the channel processes of widening or incision (Poff et al., 1997; Prestegard, 1988; and Hammer, 1972).

As peak flow rates increase, higher depths and higher velocities are present within the stream channel. As evident by the mechanics of Shields equation (Shields, 1936), the larger, flashier flows will move larger sediment and therefore more sediment downstream or unto the floodplain as the stream adjusts from its previous, natural state, leaving behind larger particles on the stream bed.

The Hammer Number and the coarsening of characteristic sediment

In addition to coarsening of D_{50} with increased RBI, D_{50} also tended to increase with increasing H. Although this could be due to the higher flows that are implied by increased RBI, bankfull flow rate is often considered to be the channel-forming flow (Allen et al., 1994), or the flow that moves the most sediment, and so it is not surprising that Hammer number and D_{50} are positively correlated. In fact, the same mechanics of Equation 2.1 apply here. However, the effect of Hammer number on D_{50} may be the result of a lurking variable, namely RBI, which was significantly correlated to both D_{50} and H.

5.5 HYDROLOGY: A WINDOW TO STREAM FLOW FUNCTION

5.5.1 Richards Baker flashiness and the Hammer Number

Stream flow measurement of the system proved to highlight some dramatic differences between stream behaviors. One expected behavior was that streams with smaller watershed areas had flashier flows (as found in Baker et al., 2004). However, no such pattern was apparent with our data. Other factors could account for this such as imperviousness. The effect of impervious area is a well-documented factor leading to stream flow flashiness (Allan, 2004; Baker et. al., 2004; Booth et al., 2004; etc.). However, there is typically a threshold in such analysis. For watershed imperviousness, that threshold has been found to be about 6% impervious area (Baker et al., 2004), but ranges from 4 to 9% (Brabec, 2009; Hicks and Larson, 1997). Only two of the SCPDP sites fall in the grey area between 4 and 9% imperviousness (Huckleberry Branch, at 4.17%, and Jeffries Creek USGS, at 5.92%), and none above the 9% threshold. With only two of the sample sites falling in the range that may show an effect on stream function, there was not enough variation in this dataset to determine if correlations exist. As the expected behavior of RBI with catchment area did not occur, and there was not sufficient variation in TIA to determine its effect on the watershed, other sources of variation in RBI had to be determined. Such cases include general land disturbances such as agriculture (Fongers et al., 2007; Baker et al., 2004). Such trends were not apparent. However, RBI was greatly affected by wetlands within the catchment and entire riparian buffer, as discussed in section 5.1.1.

While the effect of wetland area within the riparian buffer has already been discussed, other metrics of land cover seemed to have little or no effect on measures of stream flow function such as RBI or H. However, the correlation between Hammer number and RBI ($R=0.68$, $p=0.007$) holds significant promise for the prediction of flashiness without long-term datasets. Being able to identify an

impaired stream quickly could prevent further degradation of that stream, and holds the potential for significant cost savings. In fact, Hobs and Harris (2001) showed that as the physical stream continues to degrade, the cost of stream restoration drastically increases.

5.5.2 Bankfull Recurrence and Stream flow Function

Bankfull occurrences per year for the Pee Dee Region tended to be much higher than most documented recurrence intervals (Metcalf et al., 2009; Wilkerson et al., 2008; Castro and Jackson, 2001; Wolman and Miller, 1960) while falling within the a conceivable range of others (Jayakaran and Ward, 2007; Sweet and Geratz, 2003). For a summary of these studies, see Table 5.1. The differences among the recurrence intervals are due to variations in the methodology of determining recurrence intervals, particularly in regards to annual series log-Pearson type frequency analysis, annual peak series log regression analysis, and time duration analysis, of which the log-Pearson type frequency tends to yield higher frequencies (Powell et al., 2006). Powell et al. (2006) also indicated that the use of the annual series regression analysis does not yield recurrence intervals below 1 without fitting a regression. This is evident in the studies in Table 5.1, excluding Jayakaran et al. (2005) and Sweet and Geratz (2003), where the recurrence interval does not go below 1 (yrs). Despite similarities between the SCPDP study and others, the bankfull occurrences noted in this study are not reported as recurrence intervals because a long-term datasets are needed to calculate statistically valid recurrence intervals. Therefore bankfull occurrence presented in this study is only a preliminary estimate of a to-be-determined recurrence interval, and is speculative at best. Another possible reason for high bankfull occurrences reported in this study is that some of the study sites were essentially located in woody-wetlands whose floodplains are inundated for long periods of the year, suggesting that some of these streams classify as wetland streams and therefore should be analyzed separately.

Table 5.1 – Summary of long term studies that report return period of bankfull flow rate in several regions across the US.

Author(s)	Publication Year	Region	Return Period (yrs)
Metcalf et al.	2009	FL, GA, & AL	1 – 1.4
Wilkerson	2008	Eastern US	1.5
Jayakaran et al.	2005	Ohio	0.2 – 5.7
Sweet and Geratz	2003	NC Coastal Plains	0.11 – 0.27
Castro and Jackson	2001	Pacific Northwest	1 – 2.95
Wolman and Miller	1960	Maryland	1.01

SCPD sites with lower or no bankfull occurrences per year typically scored low on the QHEI. The low-scoring (QHEI) streams had similar stream channel shapes (Type II/III¹⁶) that were essentially rectangular, with vertical banks that would be considered to be prone to bank instabilities. Despite efforts to select stable streams, some stream sites (particularly Little Fork Creek and Thompson Creek) were subject to instabilities in the system due to historic but sudden land cover change. These instabilities scoured the stream bed resulting in a deeper incised channel and hydraulic disconnection from the legacy floodplain. This sequence of events has been well documented in various Channel Evolution Models (CEM) by benchmark studies conducted by Trimble (2009), Thorne et al. (1996), Simon (1989), and Schumm et al. (1981). The geomorphology of both Thompson and Little Fork Creeks closely resembles the Stage II/III of the streams reported in these studies. A similar disconnection of channel from floodplain is common in many modified ditches and streams (Jayakaran et al., 2010; Jayakaran and Ward, 2007), and could also be the case at Thompson Creek in particular, whose watershed is particularly influenced by agricultural land cover (with 40% agricultural land cover within the entire catchment), and whose floodplain has been actively cultivated for several decades.

¹⁶ Referenced from the Incised Channel Evolution Process found in Schumm et al. (1984)

5.5.3 Fluctuation of Temperature Variation with Flow Characteristics

Bankfull flow rate and TVI

A negative correlation between Q_{bkf} and TVI could be attributed primarily to the size of the stream. Smaller streams with shallow flow depths are prone to be influenced by ambient temperature fluctuations compared to deeper streams whose lower depths are thermally further from the atmosphere. Another important factor is base flow. In fact, stream discharge has been defined to be a driver of stream temperature (Poole and Berman, 2001), where they found that as stream order increased, stream discharge had a more profound effect on temperature. Factors shown to affect stream temperature were extent of riparian shade, presence of inflowing tributaries, and presence of phreatic/hyporheic groundwater inputs (Poole and Berman, 2001). Poole and Berman (2001) reported phreatic groundwater and riparian shade having a greater effect on the temperatures of lower-order streams while hyporheic groundwater tended to have more of an effect on higher order (5+) streams. They also found that tributaries tended to influence the temperatures of 3rd-and-4th order streams (Strahler, 1957) the most, while effects of tributaries on 1st and 2nd order streams were smaller. Those streams of order 5 or larger were the least affected. When these general principles are applied to the observation made in this study of increasing values of TVI with decreasing Q_{bkf} , it may indicate two distinct findings. The first is that stream temperatures in the SCPDP tend to be more affected by variation in phreatic groundwater and riparian shade than other thermal inputs such as hyporheic groundwater. Secondly, changes to factors that affect smaller streams occur at a greater scale or more frequently than changes that would affect larger streams. Further research is needed to evaluate if these other driving factors should be accounted for in order to accurately derive a more predictive model for stream temperature variation based on a few environmental variables.

RBI and TVI

The positive correlation between RBI and TVI could be due to several reasons. A high RBI suggests greater depth fluctuation and therefore more influence by ambient temperature fluctuations. Also, RBI is affected by the relative size of its base flow to its peak flows. Streams with higher base flows would have lower RBI's (Baker et al., 2004). These same streams are more influenced by groundwater inputs which are less susceptible to temperature changes (). Also, areas that have higher RBIs due to higher percentages of modified landscape may also tend to have higher TVIs due to the loss of vegetation and therefore transpiration, which results in much greater heat dissipation than simple soil evaporation.

5.5.4 The relationship between QHEI and Calculated Bed Load

The positive correlation between QHEI and bed load flux must be examined in a broader context to better understand the relationship. Previously-reported inverse correlations between QHEI and W_{bkf} , D_{bkf} , and A_{bkf} , and positive correlation between QHEI and slope suggest that QHEI scores tend to decrease as you move downstream. Although not explicitly stated in literature, this would support Hrodey et al.'s (2009) findings, in which catchment area, upstream forested land use, stream length, and QHEI explained trends in fish abundance. Fish abundance aside, these same variables affect QHEI. As stream length increases, catchments grow larger, and sediment fine (Dade and Friend, 1998), the effect of woody materials becomes less noticeable. Velocity, slope, and D_{50} also tend to decrease as you move downstream. As each of these components increase, so does the prediction of bed load flux. Therefore, this positive correlation between QHEI and predicted bed load flux not only illustrates the bias towards headwater streams of both QHEI and empirically derived bed load flux, but also helps to validate the respective datasets.

6 CONCLUSIONS

Understanding the physical processes and components of a system is possibly the first step to understanding any natural system as a whole. In stream systems, such processes influence the transport of nutrients, habitat condition, and the mobility of populations within the stream systems and throughout the riparian area. Results from this study lay a foundation for the derivation of MAFs for the Pee Dee Region. However, the value of this study reaches far beyond merely laying the groundwork for MAFs in the region. These results provide valuable information for stream restoration and stream condition predictions, while helping provide a strategy for similar studies elsewhere.

The regional curves derived in this study provide critical insight into stream function, providing a model that scientists and engineers can use in the classification and restoration of streams in the region. These relationships add to an existing framework of hydraulic geometry relationships (Metcalf et al., 2009; Jayakaran et al., 2005; Cinotto, 2003; Sweet and Geratz, 2003; and Doll et al., 2002; Castro and Jackson, 2001; Leopold, 1994) that will continue to expand into many other regions.

As expected, metrics of flow rate (H and RBI) were found to be influenced by landscape, as has been determined in other studies (Baker et al., 2004; Brabec, 2002). The average CN at smaller scales (1000 m and 2000 m riparian buffer) was found to increase the magnitude of bankfull flows relative to watershed area (H), as also found by Pizutto et al. (2000) and Hammer (1972). Higher CNs in the SCPDP were linked to the prevalence of agricultural and development in the watershed. Therefore an increase in a combination of these land cover classes can be the cause for such increases in H. However, this was not the only source of variation in flow characteristics, as both Hammer number and RBI decreased with increased wetland prevalence (at entire riparian buffer and catchment scales).

As anthropogenic influences increase in the region, and more land is disturbed (i.e. CN rises), the importance of preserving and protecting wetlands within the system becomes more critical. The incorporation of wetlands into stream restoration techniques in SCPDP region (and similar regions) will serve as a vital tool in the maintenance and preservation of these stream systems.

Bankfull occurrence was more frequent in the SCPDP region than reported in other areas of the country (Metcalf et al., 2009; Cinotto, 2003; Doll et al., 2002; Castro and Jackson, 2001; etc.). However, the number of bankfull occurrences was very similar to the bankfull recurrence intervals reported in Sweet and Geratz (2003), a study conducted in the NC coastal plain region just north of the SCPDP study area. Reasons for such high bankfull occurrences in this study are inconclusive at this point, but may be due to the prevalence of wetlands within the study area. The negative relationship found between CN and bankfull occurrences was intriguing, but do not contradict to past studies (Booth and Jackson, 1997; Hammer, 1972). As stated by Graf (1975), the development of land (construction), results in sediment production as much as 30 times over normal bed load fluxes that enlarges the floodplain surface by as much as 270% simply by deposition of new sediments. Graf (1975) also states that once the construction stops and the sediment load reduced, impervious surfaces increase runoff and result in incision of the relatively new aggraded sediment. In other words, development causes channel incision and widening (Booth and Jackson, 1997; Hammer, 1972; Leopold, 1968). The conversion of natural lands to agricultural land in the past supplied the initial sediment input and was sustained as active agricultural practices continued. However, as agricultural lands slowly reverted back to forest through the 1900's, there was a corresponding decrease in available sediment for transport. Already impacted soils, having higher impervious values than are typically unaccounted for (Booth et al., 2004), have higher surface-flow rates. Without the sediment supply that reshaped them, these streams incise (Graf, 1975). Over time, they could conceivably incise to the point where they are no longer connected to their floodplains on a 1-to-2

year basis. The impacts of past land cover on stream systems is not a new concept. Harding et al. (1998) found that land cover 50 years ago was a better indicator of biological diversity than the land cover of today, a finding that could be relevant to physical stream function. Thus, the influence of past land cover changes on current stream system function will be incorporated into future analyses.

The increase in TVI with increases in wetlands at the a smaller scale (1000 m riparian buffer) may be explained by the notion that those streams with associated wetland complexes tend to be better connected to their floodplains, suggesting stable channels that are not as influenced by groundwater input. These wetland streams are primarily dependent on surface water input, which is much more susceptible to seasonal air temperature variation than the relatively consistent groundwater contributions. These are developing hypotheses and further investigation, including the separation of surface water inputs from phreatic and hyporheic groundwater inputs (as in Poole and Berman, 2001) would be a necessary step in the determination of sources of such variation differences.

The downstream fining that occurred in each of the unimpounded reaches and coarsening that seemed to occur immediately downstream of such impounds were concurrent with literature (Dade and Friend, 1998; Kondolf, 1997). This reversal of the trend of downstream fining results in water starved for sediment. Instead of energy being dissipated on smaller diameter particles that would be moved naturally in the system, this “hungry water” moves larger particles that used to characterize a more stable component the stream bed; thus, incision occurs causing bed incision (Kondolf, 1997). In fact, Kondolf (1997) reported that incision was most pronounced in rivers with finer bed material. This means considerable consequences may occur in most streams in the SCPDP, whose bed substrate are typically dominated by sand particles (<2 mm). The lingering effects of such permanent structures may help to explain much of the variation in the normalized bed load flux within the SCPDP region, which is riddled with impoundments throughout the stream network. Such incision

may also be an effect of RBI and Hammer number increases, which was found to positively correlate to D_{50} .

The effect of watershed land cover type and scale on the physical stream system is a promising predictor of stream flow magnitude and behavior, as well as stream dimension and other physical properties. Such findings provide insight into sources of variation in stream flow function and lay the groundwork for the determination of an MAF in the SCPDP region. Not only this, but the findings outlined in this study will begin to define the baseline stable stream for this region, and helps to ensure that no unstable stream system is used in the SCPDP MAF development.

APPENDICES

APPENDIX A1: Environmental Flow Regimes

Maintaining ecology while continuing to meet human needs

Note: This section is included in the appendices elaborate on subjected alluded to in the text. It supplies a brief synopsis of many different ways of establishing environmental flow regimes (and the like). If the reader desires to know more about EFRs, their alternatives, and how they are determined, you are encouraged to read this section. However, this is strictly supplementary. More in-depth discussions can be found in those papers that are referenced throughout this appendix.

A.1 TYPES OF ENVIRONMENTAL FLOW REGIMES

A.1.1 Minimum Allowable Flows

The determination of MAFs is one widely known attempt to address such ecological problems. Minimum allowable flows can be determined using a combination of many factors, including, but not limited to, historic discharge, stream geomorphology, ecology, land use, and water quality (Scatena, 2003). The determination of MAFs can be as simplistic as identifying required stream depths through observation, or they can be as intricate as the combining all meaningful parameters. Even within a certain locale, variation in stream morphology and changes in land use throughout the catchment area can cause determined MAFs to change considerably within a given topography or ecoregion (Scatena, 2003). However, the relatively recent identification of the need for hydrologic variance (i.e. the importance of high, medium, and low flows), has resulted in a push for towards other methods of determining environmental flows (Acreman and Dunbar, 2004).

A.1.2 Look-up Tables

Look-up tables are the most simplistic and most commonly used method in determining environmental flows. Although look-up tables often determine MAFs, they add additional components to the flow scheme that push for more variation. Often, this method is used below flow-control structures as a simple method of determining proper environmental flows downstream of these structures. Although fairly straightforward, there are three separate approaches that can be taken. The first is entirely based on trial and error, with an environmental flow regime that is strengthened over time by observations. The second is based strictly on eco-hydrologic¹⁷ observations, with little thought of convenience. The last uses existing eco-hydraulic data as its

¹⁷ Eco-Hydrology- a field that emphasizes the relationships between ecology and hydrology (Hence: *eco-hydraulic* data is a combination of both ecological and hydrologic data)

grounds for determining environmental flows. Although there are several different methods that exist throughout the US (the Tenant Method in Tenant (1976)) and UK (the *Index of Natural Low Flow* discussed in Barker and Kirmond, 1998), perhaps the most common is known as the *Tenant Method*. (Acreman and Dunbar, 2004)

The Tenant Method

The *Tenant Method* (also known as the *Montana Method*), uses wetted width, water depth, and velocity to model the physical, chemical and biological factors within a stream system (Arthington and Zalucki, 1998; Tenant, 1976). Tenant (1976) separated flow values by their preservation of habitat and suggested percentages of mean annual flow. By maintaining the 10th, 30th and 60th percentiles of mean annual flow, Tenant concluded that different types of habitat (named *short term survival*, *annual survival*, and *excellent-to-outstanding*) can be preserved (Arthington and Zalucki, 1998). Tenant (1976) also noted that such allocations would be best in *pristine*¹⁸ streams, where no diversions of stream flows have occurred, specifically in areas of the mid-western and western United States where the research on the Montana Method had been conducted. This area includes multiple transects along 11 streams throughout the Midwestern and Western United States (not actually in Montana), and so its use in other eco-hydrologic settings is cautioned (Acreman and Dunbar, 2004; Arthington and Zalucki, 1998).

Other Methods

Orth and Maughan (1982) described these flows similarly to the Tenant Method, stating that 10% of mean annual flow provides suitable habitat short time periods, 30% flow provides what was characterized as *good habitat*, and 60% (or more) of the mean annual flow provides the enough quality habitat to be characterized as *optimum habitat*. In addition to such flow allocation, Orth and Maughan

¹⁸ A stream that remains unaffected by anthropogenic activities.

(1982) recommended a 200% mean annual flow as an occasional *flushing flow*. Many other additions and revisions to this method have occurred over time. One such method increase the percentiles to the 20th, 50th and 80th percentile of mean annual flows (Arthington and Zalucki, 1998; Arthington et al., 1992).

In a study by Matthews and Boa (1991) in Texas, it was found that the use of percentage of mean yearly flows often resulted in environmental flows that were too high. Other criticisms of the Tenant Method included use of cut-off points, the method's suggested scheduling of flows, and its limited geographic applicability (Arthington and Zalucki, 1998; Richardson, 1986; Stalnaker and Arnette, 1976).

Despite lacking information on the specific effects of flows on fish habitat, the Tenant Method and other look-up table methods remain advantageous during the early planning stages of stream analysis, as it requires no field surveys and is therefore less time and resource intensive than some of the methods that remain yet-to-be discussed (Acreman and Dunbar, 2004; Orth and Maughan 1982).

A.1.3 Desk Top Analysis

Desk top analyses tend to focus more on data in their approach, often using a modeling method to predict future data. Although many use the full eco-hydrologic spectrum of data, some focus only on the hydrology of the system.

Range of Variability Approach

The Range of Variability Approach (RVA) is strictly a hydrologic desk top analysis method (Richter et al. 1996; Acreman and Dunbar, 2004). This method compiles flow data indexed by magnitude (high or low flows), timing (in this case, monthly), frequency (number of events per time), duration (length of time of the event), and rate of change of discharge. The data is then compiled over several

years and standard deviations were calculated in the median quartile. Because of the lack of ecological data, it was assumed that the indicator of hydrologic alteration (IVA) was a data point that fell outside of plus or minus one standard deviation from the median (Acreman and Dunbar, 2004; Richter et al. 1996).

Lotic Invertebrate Index for Flow Evaluation

The Lotic Invertebrate Index for Flow Evaluation (LIFE) method was developed in the UK as a method to determine environmental flows using invertebrate data (Acreman and Dunbar, 2004; Extence et al., 1999). This method uses invertebrate species and abundance indices and inserts them into a metric that ranks different species of lotic invertebrates based on their sensitivity to water velocities. Recommended flow values are then calculated to achieve optimum water velocities for target species (Elliot et al., 1999).

Hydrological Index Approach

Another desktop method was developed for use in South Africa (Acreman and Dunbar, 2004; Hughes and Munster, 2000; Hughes and Hannart, 2003). This uses a hydrological index (Equation A1) and compares it to the percentage mean annual runoff values necessary for different discharges within the environmental flow regime (Hughes and Hannart, 2003).

$$\text{Hydrological Index (HI)} = \frac{\text{Coefficient of variation of flows}}{\frac{\text{base flow}}{\text{total flow}}} \quad (\text{A1})$$

Although desktop methods seem more reliable than of look-up tables (specifically by relying on collected data rather than rules-of-thumb), they assume that many biotic components are solely connected to hydrologic data in order to simplify data analysis (Arthington, 1998), which may not be the case. Also, because time series isn't necessarily an independent variable, many statistical methods can be invalid due to assumptions made in classical statistics (Acreman and Dunbar, 2004).

A.1.4 Functional Analysis

Methods categorized under *functional analysis* take a broader approach by investigating the connections between hydrological analysis, hydrologic rating, and biological data in an ecosystem. Commonalities among these methods include habitat rating (for quality) for target species and *expert analysis*, typically involving a team of experts in fields relating to hydro-geology. (Specific requirements for the selection of such teams vary by method.) (Acreman and Dunbar, 2004)

The Building Block Methodology

South Africa, in particular, has made good use of this type of method in their implementation of the Building Block Methodology (BBM), developed by Tharme and King (1998). The BBM was developed in South Africa in response to the pressing need for potable water drawn from surface water resources (Arthington, 1998). The BBM is designed for simple and rapid application (typically within one year) that ensures the maintenance of ecological health in regulated rivers (King and Louw, 1998; King and Tharme, 1994). It is a relatively inexpensive methodology, and its explicitly structured guidelines yield results in a consistent fashion (Arthington, 1998). Although the BBM is designed for rapid application, it was developed from a long-term dataset (refer to King and Tharme (1998)).

The BBM was designed under 3 important assumptions. The first is that river biota can either survive or thrive in both low flow and flood conditions that occur naturally in a *virgin* (pristine) stream. The second assumption states that the environmental flows maintain both streambed integrity and biological processes within the stream only if they can emulate the most critical components of natural flow. These critical components include, but are not limited to, velocity, discharge, and flow variation. The last assumption is that certain discharges tend to influence channel morphology and stream biota more than others. (Arthington, 1998)

The explicitly structured format of the BBM process can be found in the manual for the BBM (King et al., 2000). This process produces a monthly environmental flow plan that results from the collection of quantitative flow ecological data and expert review¹⁹. An integral part of the monthly environmental flow plan, is BBM's use of flow rationing. This is necessary component of environmental flow planning, especially in arid and semi-arid areas, like much of South Africa (Arthington, 1998). From this information, a series of *Instream Flow Recommendation* (IFR) tables are made to help better consistently portray the panel's findings (Arthington, 1998). It also helps simplify these findings for legislative and legal purposes (a consideration for the Pee Dee Project).

One of its most apparent strengths is BBM's all-encompassing approach, considering the needs of abiotic and biotic factors, water supply, and recreational needs (Arthington and Lloyd, 1998). Also, the BBM is comprehensively outlined and provides thorough guidelines that result in an end product in the form of IFR tables. This standardized method of reporting conclusions results in end data that "facilitate the communication of quantitative flow recommendations to engineers and planners" (Arthington and Lloyd 1998; Tharme 1996). Another strength is its versatility, as it can be applied consistently to a multitude of different riparian systems and even estuaries (Arthington, 1998). The BBM is has now been incorporated into South African Water Law (Services Act of 1997 and the National Water Act of 1998) (Arthington, 1998).

A major limitation of the BBM is the definition of *current state* (Very Low, Low, Moderate, High, Very High) and the determination of when goals for *desired state* are achieved, all of which are subjective assignments of interpreted stream health. Even with guidelines, these classifications are simply

¹⁹ Expert reviews first require the convening of an expert panel. This panel typically consists of respected scientists within the eco-hydraulic field in specific expertise in areas such as physical sciences, hydrology, hydrogeology, geomorphology, ecology, entomology, fish biology, botany, and others (Acreman and Dunbar, 2004). Some examples of *expert review* would be the examination of the stream banks for evidence of instability or erosion, the existence of vegetation and other habitat, or other observations that examine the state of individual components of the riverine system (King et al., 2000).

qualitative and have a tendency to vary among researchers (Arthington and Lloyd, 1998). Also, because of the BBM's rapid assessment, it is highly dependent on professional judgment, and would be a much more concrete method if more data were taken over a longer period of time (Arthington and Lloyd, 1998). However, these limitations tend to be common among all functional analysis methodologies due to their dependence on expert review. McCosker (1998) suggested modifications that would strengthen the BBM's results. These included adding a wider range of ways to present findings (other than only IFR tables) and having flow values available to the researchers electronically.

The Flow Events Method

The Flow Events Method (FEM) (Stewardson and Gippel, 2003) focuses on the variable nature of river discharge and its implications with the *ecological niche concept*²⁰, which has been used as a foundation for other environmental methods (the most well-known being PHABISM) (Acreman and Dunbar, 2004). The FEM's procedural method includes the headings of *list ecological factors, define flow events, model hydraulic relations, evaluate flow management scenarios, and specify environmental flow rules or targets*. The specific procedure of the FEM can be found in *Incorporating Flow Variability into Environmental Flow Regimes Using the Flow Events Method* (Stewardson and Gippel, 2003). Despite a defined procedure, the outcomes are more catered to modeling applications rather than implementation (Acreman and Dunbar, 2004). However, the authors of the FEM suggest the use of an expert panel, much like the BBM, to interpret the FEM's river assessment and implement an environmental flow plan (Stewardson and Gippel, 2003).

Acreman and Dunbar (2004) point out that the methods of functional analyses rely heavily on the knowledge of eco-hydrologic relationships that are not yet fully understood. So although these

²⁰ The *ecological niche concept* assumes that species and species-interactions within a given habitat reach equilibrium in variable flow system (Hutchinson, 1957).

methods merit conceptual strength, they require facilitators, like the expert panel of the BBM to turn the information gathered into an environmental flow plan to be implemented.

A.1.5 Hydraulic Habitat Analysis and Modeling

Hydraulic and habitat analysis modeling approaches habitat rating from a hydraulic perspective, evaluating target habitats (derived from target species' needs) based on their availability and quality at particular varying flow stages (Acreman and Dunbar, 2004). Perhaps the most commonly known is the Wetted Perimeter method (WPM).

The Wetted Perimeter Method

The WPM is a graphical approach that determines the point, or *break point*, where small changes in water level result in large changes in wetted perimeter (Gippel and Stewardson, 1998). In other words, the *break point* is the point where an increase in water depth results in a minimal change in wetted perimeter, where the wetted perimeter is potential habitat.

In North America, breakpoints determined from the wetted perimeter technique were compared by Stalnaker et al. (1995) to local fish populations in order to attain optimum wetted perimeters within riffles²¹. Although flow depth (and/or flow duration percentile) is an integral part of the wetted perimeter method, it is also important to consider velocities. Though some habitats may be submerged at certain flow levels, the water velocities within these habitats may be unsuitable for species that would utilize them (Orth and Maughan, 1982).

The widespread use of the WPM has led to multiple studies attempting to distinguish optimum wetted perimeter, which seem to change considerably by geographic region (Reinfelds et al. 2004; Gippel and Stewardson 1998; Orth and Maughan 1982). However, this could be attributed to the

²¹ In most wetted perimeter measurements, riffle cross-sections are used as opposed to other stream cross-sections due to their susceptibility to low flows (Stalnaker et al., 1995).

fact that no objective method has been found to determine the breakpoint. Rather, it is subjectively determined by the researcher and fueled by the scale chosen for its' determination (Gippel and Stewardson, 1998).

The issue of determining a break point is further complicated by the many different curve shapes that result from various stream cross-sections. This issue is highlighted by Gippel and Stewardson (1998), who found that use of multiple wetted perimeters along a stream tended to make breakpoints harder to distinguish, while relying on a single cross-section is far from ideal (Gippel and Stewardson, 1998). However, despite these issues, the wetted perimeter method remains appealing a tool for quick evaluations of multiple sites within a watershed (Arthington and Zarlucki, 1998).

The Instream Incremental Flow Method

Another hydraulic habitat analysis and modeling method is known as the Instream Flow Incremental Method (IFIM) (Stalnaker et al. 1995). The IFIM was developed through the collaboration of the Cooperative Instream Flow Service Group as part United States Fish and Wildlife Service (USFWS) as tool to be able to accurately and efficiently provide recommended flows for streams in order to maintain ecological stability. This method uses stream depth as a tool to predict velocity, flow, and other physical parameters that help to accurately estimate amount of usable habitat in a given stream reach. This method also incorporates water quality, food and energy sources, and biotic interactions (Stalnaker et al. 1995). IFIM targets a particular species, or a set of sensitive species, in order to more efficiently analyze flows necessary within a given habitat. For each of these species of concern, habitat-suitability curves are derived. Habitat-suitability curves are actually two curves that are combined. The first curve illustrates a relation between habitat and flow rate. From this first curve, suitability-of-habitat curves for a particular species are derived. The suitability-of-habitat curves compare suitability (ranging from zero to one), to depth, velocity, and channel sinuosity index (Stalnaker et al., 1995).

A program known as the Physical Habitat Simulation or PHABSIM (II) is used to transform hydraulic datasets into some equivalence of habitat that can be used by a particular species in a given stream reach (Stalnaker et al., 1995; Orth and Maughan, 1982). Each stream-reach, or *cell*, as determined by PHABSIM II is then given its own ranking, or *factor of suitability*.

An inherent limitation of this method is the focus on fish species as the sole biotic indicator. Whatever the case, the PHABSIM II software provides a consistent way for IFIM to analyze and interpret data (Arthington and Zalucki, 1998).

The physical habitat modeling approach used in the IFIM has begun to see worldwide use (Parasiewicz and Dunbar, 2001). However, often the cost of improvement is complexity. In the future, many hope to see similar methods that utilize more general rules (Acreman and Dunbar, 2004; Lamouroux and Capra, 2002).

A.1.6 A Progression in EFR strategy - The Holistic View

Holistic approaches are a relatively new type methodology that attempt to address issues of inaccuracy, relevance, expense, and resource intensity (Arthington and Zalucki, 1998). These methodologies address the entire ecosystem, including wetlands, groundwater, hydrology, water quality, flow-sensitive species (e.g. fish, macro-invertebrates, macrophytes, and algae), and many other components of the riparian system (Acreman and Dunbar, 2004).

Streamflow variability is of particular concern in holistic methods. Many holistic approaches treat streamflow variability as a master variable that is the driver behind many other ecological variables within the riparian system (Richter et al., 2003). Although differences in MAFs and natural flow are apparent (Richter et al., 2003), the time scales of these variations are of considerable concern. These

variations can be measured on a basis of hours, days, months, or seasons with some variations, while relative extrema may occur once or twice every couple of years (Poff et al., 1997).

The holistic concept also tends to place a greater emphasis on expert opinion than modeling. This is considered a way to incorporate entire-ecosystem-level assessments into the environmental flow (Acreman and Dunbar, 2004). This concept of expert review has also been incorporated into other methodologies (like the BBM).

Although only loosely defined, the process starts with the individual experts gathering data within their particular field and reporting their findings to the panel. The panel then constructs an environmental flow plan and brings it to the public in order to ensure public interests are accounted for. The environmental flow plan is then adjusted based on public interests and implemented. Data collection continues and is analyzed by the expert panel on given time intervals. The expert panel then adjusts the EFRs accordingly until the data suggests an optimum EFR has been reached. (Acreman and Dunbar, 2004; Arthington and Zalucki, 1998)

Most holistic techniques have the potential to be integrated in some form into existing methods. However, some are explicitly defined processes with stand-alone methodologies, including the Expert Panel Assessment Method (EPAM), the Scientific Panel Assessment Method (SPAM), and the Holistic Approach (HA) (Arthington and Zalucki, 1998).

The Expert Panel Assessment Method

In a study conducted by Swales and Harris (1995) on 6 streams in Southern Australia, streamflow was controlled below dams to 10, 30, 50 and 80 of daily flow duration percentiles. This method was designed under the objectives of 1) the model must be widely applicable 2) the model must be inexpensive and 3) the model must not require extensive field measurements. As a result, EPAM uses only one indicator of river health: fish. The EPAM assumes that using fish as an indicator of riverine

health is a cost-effective and reliable method to determine river health. This is a warranted assumption because fish species have been widely accepted as an indicator for river health due to their susceptibility to a wide array of direct and indirect stressors, that (Yoder and Rankin, 1998; Novotny et al., 2005; Bedoya et al., 2009).

While most holistic methods utilize a single expert panel, this method uses two. This strengthens the values assigned to ecological components of river health in order of importance. The environmental components, which are not explicitly defined, are ranked based on their importance in areas of indigenous fish survival and abundance, adult spawning requirements, fish passage between pools, juvenile recruitment, feeding availability and growth rates. (Swales and Harris, 1995)

One of the major strengths of EPAM is that it requires a multidisciplinary approach by established experts who use their best judgment to determine a necessary plan of action. Also, this method is site-specific, which means that every approach will be tailored to a particular stream of riparian system (Arthington, 1998). One of the limitations of EPAM is the psychological dynamics of the scientific group. This is especially the case in instances where certain personalities tend to dominate and/or sway the judgment of others (Arthington, 1998). This is referred to as “collective bias” (Cooksey, 1996). This was somewhat warranted by Arthington (1998), who stated that the assessment of these quantifiable values [of stream ecology] qualitatively proved to be inconclusive, as only one of the 18 sets of scores actually correlated at $p < 0.05$ (Arthington, 1998). Cooksey (1996) also criticized the selection process of experts, inciting that the selection of the scientists for the panel is a subjective process in and of itself, which is an inherent weakness in all methods that employ the holistic view. Also, Cooksey (1996) criticized the use of a ranking system, which tends to be very subjective in nature. Bishop (1996) also points out that variations in scores in the ranking system can be attributed to different specialists’ knowledge bases. Among other possible weaknesses, Arthington (1998) illustrates that this method can only be applied to riparian systems with upstream

flow control and that its own objective, requiring little data, is an inherent weakness from its inception.

The Scientific Panel Assessment Method

The Scientific Panel Assessment Method (SPAM) (Thomas et al., 1996) is a modified EPAM that attempts to remedy some of the disadvantages of its predecessor. This method involves the collection of flow data at multiple stream reaches along a regulated river (rather than just one) and includes total discharge, flood frequency, drought frequency, seasonal flow trends, and flood hydrographs. These data are then statistically related to multiple biotic and abiotic factors that include fish assemblage, geomorphology, plants (specifically trees), macrophytes and invertebrates. SPAM also broadened the analysis of the riparian ecosystem by comparing the movement of energy and carbon to flow regime rather than just comparing fish and invertebrates in macro-to-micro level habitats within a stream (Pusey, 1998).

The SPAM uses well-defined objectives that address the root causes for variations in flow while requiring few resources to accomplish these objectives. Also, SPAM employs the integration well established protocols for visual assessment, abiotic and biotic data collection, thereby validating its methods. (See *Thomas et al., 1996*, for specific procedures.) The broad range of data that incorporates various biotic and abiotic factors mentioned previously, changes in flow (timing of certain flow events, their magnitude, and frequency), and biotic responses to changes in habitat (in this case, flow elements) into the analysis, making it truly holistic. Lastly, SPAM takes a proactive approach. Not only does it identify the condition of a riparian system, but it incorporates a framework that plans the necessary steps towards mitigating existing impairments. (Arthington & Lloyd, 1998; Tharme, 1996)

Common among all holistic approaches is the dependence on the knowledge of quantitative relationships between various components of an ecosystem, which in many cases, does not exist. As a result, qualitative relationships must be formed, which are particularly vulnerable to subjective interpretation. Lastly, the estimation of percentage reduction in flows given by the method relies solely on in-channel flow depths while neglecting the maintenance of geomorphological processes, a critical component of river ecology and river health. (Arthington & Lloyd, 1998; Brizga, 1998; Bunn, 1998; Pusey, 1998)

The Holistic Approach

The Holistic Approach (HA) was developed at an Australian water conference (Brisbane Workshop, 1991) through the collaboration of South African and Australian Scientists. Its aim is to combine the analysis of an entire riparian ecosystem, with factors including, but not limited to, “source area, river channel, riparian zone, floodplain, groundwater, wetlands and estuary.” It assumes that hydraulic regime is the controlling variable for these factors, maintaining the *functional integrity*²² of the riparian ecosystem (Arthington, 1998).

The HA targets factors that are essential to the riparian ecosystem, such as specifics of the hydrological regime (seasonal flow distribution, intermittency, no-flow periods, flushing flows, and the variability of flows on monthly, seasonal, and annual time scales), aspects of fluvial geomorphology, and ecological metrics. These are then combined to produce a single modified flow regime on a month to month basis (defining both maximum and minimum flows), which are tested and modified as necessary. Optimum flow plans are assumed to maintain water quality, geomorphology and stream biota when followed correctly. As this process is meant to be iterative, researchers would refine flows below control structures until biological and geomorphological data

²² *Functional integrity* is defined as the integrity of genetic and species diversity, community structure, and ecosystem processes (Arthington, 1998b).

suggest flows are sustaining riparian ecology. In order to do this, Arthington (1998) suggests that flows should be maintained within the historical low and high flow rate of a particular river. This being said, if overconsumption of water resources were to occur, it would be nearly impossible to sustain the riparian ecology. To remedy this, the HA assumes water in the environment *belongs* to the environment, and suggests steps be taken to relieve pressure on the water supply in periods of drought (much like the BBMs use of storage). (Arthington, 1998)

In the HA experiment, a section of Barambah Creek (Australia) was used to test a series of different flows and expressed as daily flow duration percentages. Monthly flows, habitat, reproduction/spawning, and fish passage were all evaluated in combination with wet and dry season flows in order to assess the ecological integrity of the river for different flows. High-flow ‘bursts’ (to promote fish migration and pollutant flushing) are proposed until a modified flow regime can be determined. However, some of these very high bursts during the dry season showed the potential to ruin fish spawning habitat, as one fish species failed to spawn in the section of river being tested (Arthington, 1998). In Stage 2, visual observations of the riverine ecology at different flows are used to identify which are biologically significant. These biologically significant flows are then assessed based on levels of salinity (with many salts entering surface waters from agricultural runoff) and dissolved oxygen (Bluhdorn and Arthington, 1995).

From this method, a new concept called *scheme transparency* emerged. This involves the use of a hydraulic model that estimates flow rates by tributaries upstream of a particular reach (both regulated and unregulated) and suggests how much water should be released in order to attain the suggested modified hydrologic flow regime. The third and final phase proposes a method to provide daily flow requirements in order to fine-tune the HA. This phase seeks to accommodate ecologically sustainable flows and to “maximize net revenue”. The maximizing of revenue would be brought about by providing a detailed scheme that would depict the amounts of water that can be harvested

for irrigation in a variable surface-flow regime. The resulting trade-off curves compare environmental effectiveness with corresponding flow and cost effectiveness. On each curve, a break-point is identified, much like the break point discussed earlier in reference to the use of a wetted perimeter. The break point is typically defined by 80% of total flows originating from tributaries with natural flow regimes and the other 20% originating from reservoirs (Arthington, 1998). However, like in the wetted perimeter method, the determination of this breakpoint can lead to inconsistencies between evaluations of revenue and river discharge.

Since its inception, the HA has been applied Australia, United States, and other areas around the world (Arthington, 1998). The HA philosophy is that that water in the environment *belongs* to the environment, and that anthropogenic needs are to be met with water that is in excess of environmental needs. Environmental need is to be determined not just for the reach in question, but for the entire contributing drainage network (Young et al., 1995). Researchers such as Reeves (1994) and Richter et al. (1997) have acknowledged that the method tends to better mimic natural flows than engineered flows. The HA uses historical flows and long-term daily data to determine flow regime, assuming that anything outside the recorded flow regime is unnatural and therefore unsustainable. Lastly, the HA is adaptive, leading to ‘compromise’ with industry. (Arthington, 1998)

Although labeled holistic, the HA relies solely of hydrologic factors as the independent variables, and as such, ignores many biologic factors. Even though the method is based on quantitative data, this data must be interpreted, and therefore remains highly reliant on expert review (Young et al. 1995). Also, unlike the specific set of instructions provided by the BBM, the Holistic Approach has not yet defined a specific set of procedures, and so its results are not always reported in the same way (Arthington, 1998). This lack of specific procedures has led some to ask how exactly *sustainable harvests* and *natural flow regimes* are determined (Young et al., 1995).

APPENDIX A2: Fish Assemblage

Note: This section is included in the appendices elaborate on subjected alluded to in the text. A brief overview and analysis of a 2-year dataset and be found here. However, no discussion or conclusions were drawn do the limited nature of this preliminary dataset.

A.2.1 FISH AS ECOLOGICAL INDICATORS

Large watersheds, like the Pee Dee (with a drainage area of over 7200 square miles), are often defined by high biotic diversity. Diversity of entire fish assemblages have been linked to entire watershed evaluations of landuse, topography and size; while the investigations of smaller spatial scale, like riparian buffer, have shown to contain indicators of individual species health (Schiemer, 2000). The assessments of plant and animal assemblages have been utilized as ecological indicators for decades. However, there has recently been a shift of focus to species that are high on the trophic level, specifically fish species (Landres et al., 1998). This is because fish species depend on lower level organisms for their survival, including plants, algae, macro invertebrates, and bacteria, which are in turn dependent on their respective habitats. It is this dependence-structure that makes fish diversity and abundance a good indicator of overall stream health (Rankin, 1989; Wang et al., 1998). Although other indices of plant, macro invertebrate, and habitat quality are often used, the dependencies of fish fauna on the surrounding environment make them a “critical sensor of integrity at different [spatial] scales and thus a good monitoring tool with regard to river engineering.” (Landres et al., 1998)

A.2.2 The Dependence of Fish on their Environment

Fish are inherently dependent on their surrounding environment. Scheimer (2000) defines three ways in which fish are dependent on the ecological integrity of a riparian system: hydrological integrity, nutrient flux integrity²³ and habitat connectivity.

²³ Nutrient flux integrity refers to the ability of the riparian system to cycle nutrients between the catchment and floodplain. *Water quality* is a common indicator of proper nutrient cycling, and results of water quality tests for nitrogen, phosphorous, turbidity, and dissolved oxygen (DO) levels will often accurately predict the condition of the nutrient flux system. As such, water quality and nutrient flux are often used synonymously, and so water quality will be used for the remainder of this paper. (Vanni et al., 2001)

Under the term hydrological integrity, Schiemer (2000) indicated that ecological integrity, like any riparian system, is spatially dependent. Riparian systems can be broken up into a series of smaller ecological habitats that can be evaluated on an individual basis and as an entire system. Both surface and ground water must be evaluated as they are intimately connected to daily fluctuations due to evapotranspiration and precipitation. These fluctuations result in variations in habitat availability with water level fluctuations, changes in geomorphology of the channel bed, and even changes to disconnected water bodies within the floodplain of the riparian system. (Schiemer, 2000)

This intimate relationship between fish populations and the stream flow dynamics has been examined in numerous studies that link stream health and riparian stability, that primarily address issues of habitat and the velocities in particular habitat areas, specifically concerning spawning (Acreman and Dunbar 2004; Brizga 1998; Gippel and Stewardson 1998; Cooksey 1996; and many others).

Water quality is intimately connected to fish for obvious reasons. Perhaps the most common is the input of nitrogen and phosphorous into systems that results in algal blooms. These algal blooms then cause large variations in oxygen as they begin to die and decompose. During the day, algal photosynthesis (input of O₂) and bacterial degradation (consumption of O₂) processes maintain a constant oxygen level, but without photosynthesis at night, high microbial activity due to the degradation of large amount of dead algae causes nightly dips in DO levels, and thus, fish kills. Also, excess nitrogen in the water is known to inhibit oxygen uptake by but fish and humans (blue baby syndrome).

These same nutrient flows are linked to watershed hydrology and land use. Certain land uses, such as agriculture, can cause instream nutrient levels to increase, while other land uses (like those classified as urban) affect hydrology by leading to greater flushing flows (Richter et al. 1996 and Stein & Flack 1997; in Blahn et al., 2009). This can help flush out excess nutrients, but flow levels that surpass the

bed's resistance to shear stresses can result in channel incision. Constant low flows and lack of flow variation, however, can hinder the transfer of nutrients between the main channel, flood plain, and isolated pools (Scheimer, 2000).

Habitat connectivity, or the connection between various habitats, is a critical component for fish, especially in regards to spawning and juvenile stages. Flows that are too small may cause the stream to become intermittent, hindering fish movement, especially in regards to spawning. A similar situation of intermittency arises with dam construction and the subsequent limiting of fish movement. Flows that are too large in particular habitats, result in flow velocities that can scour away habitats or just make certain habitat inaccessible to fish that are not suited for such conditions. (Scheimer, 2000)

A.2.3 Species Diversity

The use of the diversity of biotic species to determine ecological integrity has long been a topic of ecologists' interests (e.g. Fisher et al. 1943; Gleason 1922). Many indices for species diversity have been developed in order to determine species richness of a stream system. In many cases, these indices can be used across multiple species, including, but not limited to plant species, macro invertebrates, fish, and amphibians.

Nicholson and Jennings (2004) acknowledge the importance of biotic community indicators, in particular for fish, noting their "relative sensitivity to changes" and the advantage of being able to quickly change strategies in response to particularly sensitive fish populations.

It is because of the wide use of fish diversity and other biodiversity indices (algae, fungi, macroinvertebrates) as indicators of ecological integrity that there have been so many attempts at defining species diversity. Each attempt, or index, has its own merit, but it would be advantageous to

use multiple indices to determine diversity rather than just one (Huston, 1998). The biotic diversity indices that will be summarized in this review will include the Menhinick's Index (Menhinick, 1964), Margelef Index (Sanderson, 2009), Shannon-Weaver Index (Shannon and Weaver, 1949), and Simpson Biodiversity Index (Simpson, 1949). These indices should provide an adequate base for the evaluation of fish populations in the South Carolina's Pee Dee watershed and other similar watersheds.

Before delving into these indices, we must first define two terms: *species richness* and *species evenness*. *Species richness* is defined as the measure of the amount of different species found in a sampling area. *Species evenness* evaluates the population distribution of each species in a sample area. Multiple biodiversity of these evaluation methods is classified as *proportional abundances of species* (Huston, 1998).

Margelef's and Menhinick's Indices

Menhinick's Index and Margelef's Index are classified as species richness indices that use the number of species recorded (N) and total number of species (S) as metrics for richness calculation. The simplicity of these indices is their single greatest advantage (Magurran and Philip, 2001). Margelef (1943) stated that "...diversity is a statistical function that implies no particular regularity in distribution, and in whose computation the numbers of individuals in all species are taken into account." Margelef's (A3) and Menhinick's (A4) index indices are mathematically defined as:

$$D_{Mg} = \frac{(S - 1)}{\ln(N_a)} \quad (A3)$$

$$D_N = \frac{S}{\sqrt{N}} \quad (A4)$$

Where D_{Mg} is Margelef's diversity, D_N is Menhinick's diversity, S the total number of species recorded in the sample, N_a is the total number of individuals divided by S , and N is the total number of individuals divided

The Shannon-Weaver Index

The Shannon-Weaver index was not originally used in Ecology, but was a general index that computed both diversity and evenness of a dataset (Shannon and Weaver, 1963). Later, it was adapted to analyze fish populations as early as 1968 (Dickman, 1968). The adapted Shannon's index is defined as:

$$H' = \sum_{i=1}^s \frac{n_i}{N} \ln \frac{N}{n_i} \quad (A5)$$

Where H' is Shannon-Weaver's diversity index, n_i is the total number of individuals in species i , and all other variables have been previously defined. Typically, an H' value tends to be in the range of 1.5-3.5. A major strength of this index is the combination of both species evenness and richness. However, this index requires more calculation than both the Margelef and Menhinick Indices. Also, the Shannon index is often used solely for evenness, rather than the combination of species evenness and richness. The modified equation for evenness is shown below. (Sanderson, 2009)

$$E = \frac{H'}{\ln S} \quad (A6)$$

Where E is Shannon's measurement of evenness and all other variables have been previously defined.

The Simpson Index

The Simpson index, like Shannon's Index, combines both species evenness and richness in its evaluation of a population sample. The equation can be found below (Simpson, 1949).

$$D = 1 - \frac{\sum_{i=1}^S n_i(n_i - 1)}{N(N - 1)} \quad (A7)$$

Where D is Simpson's index and all other variables have been previously defined. Simpson's index normally yields values from 0-1 with increasing diversity as you approach 0. To convert to a probability scale, one simply subtracts the index from one, yielding an ascending order where 1 is the highest diversity. This probability scale is easier to interpret. However, there is a tendency for this index to be swayed in the presence of one or two dominant species in a sample (Dejong, 1975). As a result, it is often referred to as the Dominance Index (Sanderson, 2009).

A.2.4 Trends in Fish Assemblage

Although indices are typically a good indicator of the overall health of a riparian ecosystem, care must be taken to keep this information in context with riparian scale, geographical area, time of sampling and other factors that affect fish assemblage across multiple catchments.

Matthews (1998) identifies the diversity of fish in moving waters by illustrating differences in fish assemblage across multiple river systems, including the Amazonian river basin (1,300 species), The Nida River in Poland (25 species), the Colorado River basin (32 species) and the Mississippi River basin (375 species). However, on a reach basis (200-300 meters), Matthews (1998) suggests that a typical assemblage in a stream east of the Mississippi will normally have between 10 and 30 species, based on a study on the Mississippi River Basin performed by Moyle and Herbold (1987).

Regional variations in biodiversity have been linked to amount and heterogeneity of habitat, which is in turn linked to factors such as geomorphology (catchment scale and slope) and climate. These same regional-scale factors also affect the stream hydrology, sediment dynamics, nutrient inputs and morphology of the stream, and have also have been linked to availability and quality of habitat (Richards et al. 1995). Because available habitat is proportional to wetted perimeter (Orth and

Maughan, 1982) and that catchment scale influences the relative size of a stream or river, we can infer that within a pristine riparian system and ecoregion, fish assemblage increases as the catchment scale increases. Of course, other factors that affect stream biota such as stream slope, land use, stream morphology, nutrient inputs, channelization, bed substrate, and effective load must also be considered when accounting for variations biodiversity in similar water bodies.

A.2.5 Summary

Although fishes susceptibility to stressors make them good indicators of ecosystem integrity (Bedoya et al., 2009), it is difficult to distinguish which stressors of are the most importance. Therefore, many stressors need to be included in the overall analysis of a fish population. Despite these limitations, the analysis of fish assemblage remains among the most promising methods for gaining insight into what factors have the greatest influence on riparian ecology and an indispensable tool in the determination of a flow regime for a system of concern (Bedoya et al., 2009).

A.2.6 Methods: Electrofishing

Electrofishing is a method of fish sampling that uses an anode and cathode placed in water and transmits a current between them that stuns fish momentarily for capture and identification.

Although the specific procedure of electrofishing will be discussed in the Methods section, there are some clarifications that must be made about the nature of using electrofishing as a method of statistical sampling.

When electrofishing, the current that is passed through the water and the current felt by the fish is a function of body size and shape (Dolan and Miranda, 2003). This theory is supported by other studies that have found that larger fish are easier to immobilize with lower peak power (Anderson 1995; Buettiker, 1992; Zalewski, 1985; Reynolds and Simpson, 1978). However, larger fish are

typically faster swimmers and shorter recovery times. By following procedures outlined by organizations such as the South Carolina Department of Resources (SCDNR), fish mortality can be minimized, but not eliminated. River order greatly affects the type of equipment and procedure used. This can range from backpack shockers to entire boat outfits.

There are inherent limitations of electrofishing that must be accounted for, such as visibility. Differences in turbidity have the potential of affecting what shocked fish can be seen. Some species' have tendency to float when shocked, and others have a tendency to sink. This, along with fish size, further compounds the issue of visibility. Also, because the amount of shock is relative to body size (Anderson 1995; Zalewski 1985; Buettiker 1992; Reynolds and Simpson 1978) and body type (Dolan and Miranda, 2003), electrofishing has a natural tendency to be biased toward larger fishes. The last limitation is the mortality rate, which seems to counteract its own purpose when considering that electrofishing is often used for fish species protection. However, electrofishing is widely used because of its low mortality rate and effectiveness relative to other fish sampling methods.

SCPDP electrofishing occurred with the help of the SCDNR under the direct supervision of Liz Osier. All fish species were identified by experienced personnel, and those not identifiable in the field were preserved and identified in an SCDNR lab. Both backpack shockers and boat-mounted shockers were used, both utilizing DC currents. Those sites that had low conductivity had cubed rock salt added to increase the conductivity to an acceptable level. All results were compiled and saved in a spreadsheet.

A.2.7 SCPDP Electrofishing Results and Analyses

Because of limitations in the available equipment, as well as variations in depth, velocity, turbidity, conductivity, and the extent of the dataset (currently 1-2 samples per site), electrofishing were

inherently restricted to only one sample per site per year. These results will still be reported to be taken at face value.

Raw Results

Fish shocking occurred at Black Creek near Chesterfield, Huckleberry Branch, Thompson Creek, Little Fork Creek, Juniper Creek (DNR), Little Lynches River, Hams Creek, Jefferies Creek (DNR), and Crooked Creek (DNR). Of the 9 sampled sites, the highest number of fish sampled occurred at Little Fork Creek (454)²⁴ in 2010, and the highest number of species occurred at Thompson Creek (27) in 2010. Conversely, the lowest number of species and individuals both occurred in Juniper Creek (DNR) in 2010. Margelef's Index ranged from 3.69-9.27, with the highest occurring at Thompson Creek and the lowest occurring at Big Black Creek. Menhinick's Index ranged from 0.75-1.38 with the highest occurring at Crooked Creek (DNR) and the lowest occurring at Thompson Creek. Shannon's Diversity Index (H') ranged from 0.8-3.21 with the lowest occurring at Hams Creek and the highest occurring at Thompson Creek. Shannon Evenness ranged from 0.35-1.08 with the highest occurring at Jefferies Creek (DNR) and the lowest occurring at Hams Creek. The corrected Simpson Index (i.e. 1-Simpson Index) ranged from 0.38-0.87 with the highest occurring at Little Lynches River and the lowest occurring at Hams Creek. This data is summarized in Table A2.2.

²⁴ Over 1,000 fish were caught during the electrofishing sampling of 2011 at Thompson Creek. However, not all fish have been identified at this time.

Table A2.1 – Summary of fish data and derived indices. Data shown are averages from the 2009 and 2010 May-October seasons.

	Number of Species	Number of Individuals	Margelef's Index	Menhinick's Index	Shannon-Weaver Diversity (H')	Shannon Evenness (E)	Corrected Simpson Index
Black Creek near Chesterfield	11	166	3.69	0.85	1.26	0.53	0.55
Huckleberry Creek	13	127	5.61	1.21	1.79	0.70	0.84
Little Fork Creek	15.5	427	4.40	0.75	2.08	0.75	0.59
Thompson Creek	27	446	9.27	1.28	3.21	0.97	0.80
Little Lynches River	17.5	267.5	6.34	1.14	1.95	0.68	0.87
Juniper Creek (DNR)	9.5	55.5	5.00	1.32	0.97	0.43	0.76
Hams Creek	9.5	73.5	4.16	1.11	0.80	0.35	0.38
Jefferies Creek (DNR)	16	372	4.77	0.83	3.00	1.08	0.85
Crooked Creek (DNR)	16.5	157.5	7.20	1.38	1.50	0.54	0.68
Average	15.06	232.44	5.60	1.10	1.84	0.67	0.70

Statistical Analyses

At this preliminary stage, statistical analyses yielded substantial results. All fish metrics were normal, and therefore, none were transformed. All other previously-transformed datasets were utilized in the analyses*. Significant correlations ($R \geq 0.7$) were found to exist between each fish metric and the comprehensive dataset with the exception of Menhick's Index. The number of species significantly correlated to bankfull occurrences per year ($R = -0.71$), depth ($R = 0.76$), cross sectional area ($R = 0.75$), bankfull flow rate ($R = 0.74$), and agriculture in the 200m riparian buffer† ($R = 0.83$). A non-transformed catchment area‡ also correlated to the number of species ($R = 0.77$). The number of individuals significantly correlated to RBI ($R = 0.82$), H ($R = 0.80$), bankfull occurrences per year ($R = -0.75$), depth ($R = 0.70$), bankfull flow rate ($R = 0.72$), D_{50} ($R = 0.87$), D_{84} ($R = 0.90$), CN at the 1000m buffer scale ($R = 0.74$), CN at the 2000m buffer scale ($R = 0.82$), wetlands in the 2000m riparian buffer ($R = -0.72$), wetlands in the entire riparian buffer ($R = -0.79$), and TIA in the 2000m riparian buffer ($R = 0.71$). Margelef's Index was found to significantly correlate to agriculture in the 200m riparian buffer ($R = 0.78$) and LDI in the 1000m ($R = 0.79$) and 2000m ($R = 0.84$) buffer scales. Margelef's Index was also significantly correlated to the non-transformed catchment area ($R = 0.74$). Shannon-Weaver's Diversity Index (H') was found to significantly correlate to bankfull occurrences per year ($R = -0.76$), depth ($R = 0.70$), CN of the entire riparian buffer ($R = 0.83$), CN of the catchment ($R = 0.85$), agriculture in the 2000m buffer ($R = 0.79$), and TIA in the 2000m riparian buffer ($R = 0.74$). Shannon's evenness index (E) was found to significantly correlate to bankfull occurrences per year ($R = -0.76$), CN of the entire riparian buffer ($R = 0.90$), CN of the catchment ($R = 0.91$), and agriculture in the 2000m ($R = 0.81$) and entire riparian buffers ($R = 0.76$). The Simpson Index (D) was found to

* Because all datasets were normal, it was assumed that all p-values for the following correlations were below the 0.1 threshold, as was the case for all other previously tested correlation (in section 4: *Results*).

† Recall that this was not a normalized dataset.

‡ The non-transformed catchment area was normally distributed.

be correlated to QHEI ($R=0.78$), the normalized bed load flux per year ($R=-0.81$), the average CN of the entire riparian buffer ($R=-0.77$), agriculture in the entire riparian buffer ($R=-0.76$) and so the corrected Simpson Index (1-D) showed corresponding inverse correlations.

Unlike other datasets discussed in this document, regression analyses did not occur for significantly correlated datasets. This is because such analyses would infer causation. With the dataset is currently in its preliminary stage, such inferences would be ill-advised.

A.2.8 Fish Assemblage Wrap-up

At this point in the study, the extremely high amount of significantly correlated values is promising. However, at this point in the study, any inferences from this dataset would strictly be speculation, and it will be left to the reader to decide what to make of these results.

These results will, however, be included into the much larger body of work that is the SCPDP, and will be relied upon as one of many components used to determine an acceptable MAF strategy that will aim to protect the viability of the riparian and riverine system while continuing to meet human needs.

APPENDIX A3: Copeland's Stability Curves

Note: This section is included in the appendices for the application by future researchers. Although not able to include in this document, considerable preliminary work has been done as a part of this project.

After establishing a bed load flux from a stable upstream reach, a similar downstream reach could be examined for stability using the process elaborated upon in Copeland (1994). This was done by deriving a series of curves from concentration (\bar{C}) and flow rate (Q), which will henceforth be referred to Copeland's Stability Curves. These derived curves are essentially a family of 2 curves (Width vs. Slope and Width vs. Depth) for a given flow rate, D_{50} , gradation coefficient (σ), Manning's roughness coefficient (n), area, and base width from a stable reach. Once these lines have been established, similar reaches downstream can be examined based on variations in bankfull dimensions of slope, depth, and width (where all other parameters remain the same). While this method's intention was for the remediation of streams, it can also be used to determine a stream's stability state (stable, aggrading, or degrading). By plotting a stream's width-depth dimensions of a stream that has identical flow rate, D_{50} , gradation coefficient (σ), and Manning's roughness coefficient (n), the placement of the point in relation to the width-depth curve reveals the stream condition.

In Figure A3-1, if the point that represents the stream in question falls below the red line, the stream was aggrading, if the point fell above the curve, it was degrading, and if it fell on the red line, the stream was in dynamic equilibrium (Copeland, 1994; Hack, 1960). For the derivation of these curves, Copeland (1994) and NRCS (2007) suggest the use of a computer program known as USACE SAM (Thomas et al., 2003). Since there is not always a stable upstream reach comparable to the reach in question, the NRCS Stream Restoration Design Handbook (NRCS, 2007) suggests the use of regional curves for to narrow the range width-depth possibilities.

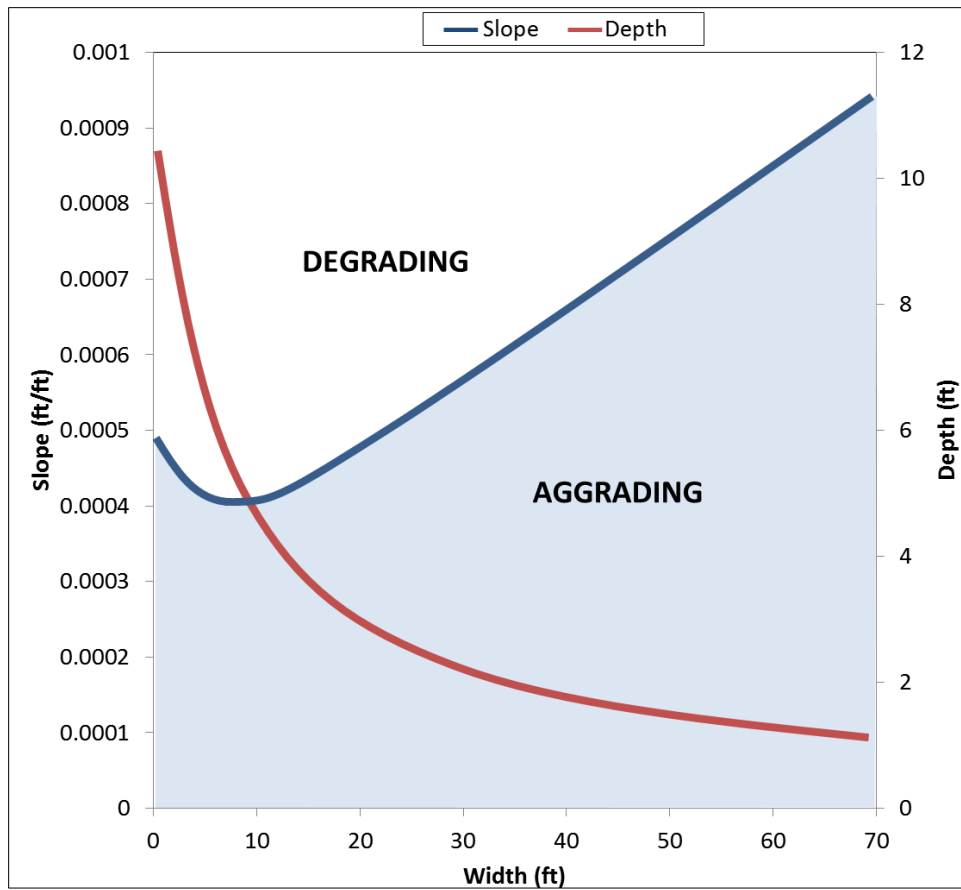


Figure A3-1: Example of a curve family developed by Copeland (1994) for a stream similar to Crooked Creek (DNR) derived through Matlab® program. If the width-depth point representing Crooked Creek (DNR)’s actually state fell above the blue line, it would be degrading; below the blue line, it would be aggrading; and on the blue line, it would be stable.

The above curve was derived through an iterative process achieved through a Matlab program. Using the parameters mentioned in the previous paragraph, slope, depth and width were iterated into the series of equations that ultimately end in \bar{C} . If the set of slope, width, and depth, output a \bar{C} within an acceptable range (typically $.01*\bar{C}$) of if the \bar{C} derived the stable reach, the set was saved as two points: (width, depth) and (width, slope). After the n th iteration has completed the resulting curve family looked something like what is pictured in Figure A3-1. The Matlab program used in the derivation of this curve can be found in Figure A.3.2, with all necessary inputs boxed and highlighted in yellow.

```

% The following program will attempt to attain a series of stability
% curves as per the NRCS (2007) handbook using iterations. This will
% hopefully do the same as the USACE SAM, but be free! This program
% was co-written with Andrew Clarke.
clear all
close all
clc

%These variables are from the Ref Reach sheet/Manning's n
% determination sheet (ENGLISH UNITS!!!):
CFD=300; % (cfs)
%this is the channel forming discharge
C_bar_ref=100; % (ppm) sediment influx from our ref. reach.
D50=0.00259; % (ft) Median Sediment . Measured from stream bed
theta=2.515; % Geometric Gradation Coefficient
n=0.2904; % Manning's n.
S=0; % Starting
Ss=2; % Side Slope

%These variables are generated, not measured
B=0; % Base of the measured stream
D=0; % Depth
index=1;
money_B=0;
money_D=0;
money_S=0;
for B=0:0.1:100;
    for S=0.0001:0.0001:0.01;
        for D=0.1:0.1:20;
            Ac=(B*D)+(D^2)*Ss; %Cross sectional area of trapezoidal
                                %Channel
            Rh=(Ac/(2*((D^2)+(3*D)^2)^0.5)+B)); %Hydraulic Radius of
                                                    %trapezoidal Channel
            V=(1.486/n)*Rh^(2/3)*S^0.5; %Avg velocity in channel
                                           % (English units)
            Fg=V/((32.1751969*D50*(2.65-1)/2.65)^(0.5)); %Froude No.
                                                            % (Eng units)
            Fg_prime=1.74/(S^0.3333); %Froude number comparison
            q_star=(V*D)/((32.1751969*D50^3)^(0.5)); %Part of
                                                        %Brownlie's Eq

```

Figure A3-2: Part 1 of 2 of Matlab® Program used to derive stability curve from stable reference reach

```

if Fg>1.25*Fg_prime
    %Hydraulic Radius assoc. w/ bed in lower regime
    Rb=0.3742*D50*q_star^0.6539*S^-0.2542*theta^0.1050;
else
    %Hydraulic Radius associated with bed in upper regime
    Rb=0.2836*D50*q_star^0.6248*S^-0.2877*theta^0.0813;
    %Hydraulic radius associated with the side slopes
    Rs=((V*n)/(1.486*S^0.5))^1.5;
end

A=Ac;    %they should be synonymous from Brownlie's....
Rg=((32.1751969*D50^3)^0.5)/1.052;    %Assumes kinematic
                                       %viscosity is 1.052

Y=((2.65-1)/1)^0.5^-0.6;
Tau=0.22*Y+0.06*(10^(-7.7*Y));
Fgo=(4.59*Tau^0.5293)/(S^0.1405*theta^0.1606);

%concentration of sediment (ppm)- Brownlie
C=9022*(Fg-Fgo)^1.978*S^0.6601*(Rb/D50)^-0.3301;
Qs=C*B*D*V;    %sediment load
Q=(1.49/n)*Ac*((Rh)^(2/3))*S^0.5; %Bankfull discharge
C_bar=Qs/(0.072*Q); %Average Concentration

if Q>=(CFD-2) && Q<=(CFD+2)
    if C_bar>=(C_bar_ref-0.5) &&
        C_bar<=(C_bar_ref+0.5)

        money_B(index)=B;
        money_D(index)=D;
        money_S(index)=S;
        index=index+1;
    end
end

end

end

end

Header=['B' 'D' 'S'];
ExcelArray=[money_B' money_D' money_S'];
xlswrite('Stream10.xlsx',Header,'Sheet1')
xlswrite('Stream10.xlsx',ExcelArray,'Sheet1','A2')

```

Figure A3-2: Part 2 of 2 of Matlab® Program used to derive stability curve from stable reference reach

Although outlined in this document, Copeland's Stability Curves were not applied to any reaches in the SCPDP because of its need for multiple sites. However, the groundwork for its future application has been laid. Since all streams in the SCPDP have been determined to be relatively stable, these will suffice as upstream stable reaches, and thus, elements of given flow rate, D_{50} , gradation coefficient (σ), Manning's roughness coefficient (n), and calculated bed load has been provided. By simply surveying downstream reaches and bed material, researchers of the SCPDP can confirm bed composition to be equivalent and thus plot the downstream reach's width and depth on its corresponding stability curve, indicating whether it is degrading, aggrading, or stable. It is theorized that the distance between the point and the curve may indicate the degree of instability. However, this was not alluded to in any literature and thus is strictly speculation.

APPENDIX B1: Levellogger® Installation

Note: This section is included for re-production at similar sites due to a successful design. This process is more recommended for smaller slower streams. Much stronger materials would be necessary for large streams. If a larger stream needs to be outfitted, the SCPDP has had the most luck in installing loggers to large trees on the bank and less luck with bridge pilings and therefore recommend selecting a location that is shielded from high velocities where the logger can be secured to a tree.

Materials

Materials necessary for installation of the flow monitoring equipment included the Levellogger, heavy-duty cord (thin Kevlar), 2" PVC pipe, a drill with a 1/4" boring bit, a locking cap, assorted 2" PVC connections (e.g. straight, 45° bend, etc.), fence posts, a heavy mallet, and heavy duty zip ties and/or metal pipe clamps.

Installation Process

Before arriving at each site, 20 feet of 2" PVC pipe was prepared by drilling 4, 1/4" holes radially every 1 inch along the length of the pipe. Once on-site, PVC pipe was cut to the appropriate size to reach the stream bottom, while remaining accessible above the bankfull flow. Using the PVC connections, the pipe was made to contour the stream bed or permanent structure as closely as possible. Cord was then cut to the length of the pipe so that the Levellogger would hang below the water surface at all times, but above the stream bed, being careful to leave enough extra cord to securely tie the PVC locking cap to the Levellogger. In what was projected to be a high-flow system, a Kevlar cord was used, whereas in low-flow systems, 50 pound test braided fishing line was used. Once the PVC pipe and connectors were assembled and the Levellogger was securely fastened to the PVC locking cap and at the appropriate level (below the minimum projected flow), the final stage of installation could begin. First, the Levellogger was removed. Then the PVC apparatus was set in the appropriate spot. A fence post was then driven into the sediment using the heavy mallet. Where deemed necessary, more than one fence post was used. The PVC apparatus was then securely fastened to the fence posts and adjacent permanent structure using an assortment of heavy-duty zip ties and pipe clamps. The Levellogger was then attached to the USB interphase and using the Levellogger 3.4.0 software, was set to take readings on 15 minute intervals, initiated with a 5 minute delay, and carefully slid into place. Finally, the pipe was capped and locked to complete the installation process.

APPENDIX B2: Equipment Photos

Note: This section is included simply for familiarization and visualization of equipment used.



Figure B2-1: Roto-Tap used in the separation of bed material.



Figure B2-2: AMS® Shallow Water Bottom Dredge used for the collection of bed material in all streams.



Figure B2-3: Solinst® Levellogger Gold used to record stream temperature and water level.

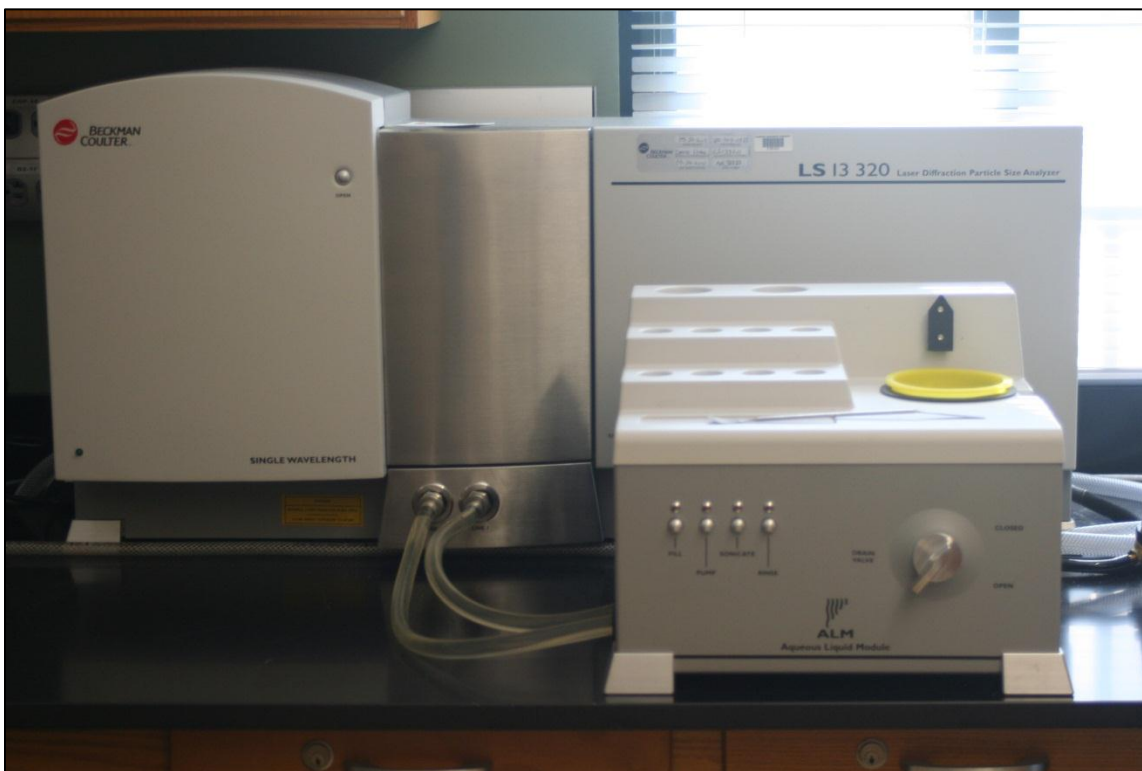


Figure B2-4: Beckman Coulter LS 13 320 Laser Diffraction Particle Size Analyzer used in the analyses of bed



Figure B2-5: Sontek® RiverSurveyor M-9 (pictured at top), RTK stationary unit (bottom right), and surveying raft on Black Creek near Quinby (bottom picture).

APPENDIX C1: Landscape Results

Note: The data summarized in the 2 tables in this appendix represent the same data summarized in Figures 4.4a-b and 4.5a-d in section 4.1, *Landscape Analyses*, of this document.

Table C1-1 – LDI, Total Impervious Area (TIA) and CN of watersheds in the SCPDP. Titles of *200*, *1000*, *2000*, and *Ent* represent the distance (in meters) from the sampled point within the buffer, while Catchment refers to the entire watershed.

Site Name (Association)	LDI					TIA					Curve Number				
	200	1000	2000	Ent	Catchment	200	1000	2000	Ent	Catchment	200	1000	2000	Ent	Catchment
Huckleberry Branch	0.05	0.02	0.02	0.14	0.16	0.41	0.14	0.07	3.35	4.17	37.0	35.9	35.1	71.0	60.4
Little Fork Creek	0.04	0.01	0.04	0.04	0.07	0.76	0.09	0.57	0.58	1.34	60.4	64.4	69.8	58.4	59.9
Jefferies Creek (DNR)	0.06	0.02	0.02	0.03	0.16	0.02	0.15	0.26	1.66	2.24	26.4	58.6	66.3	75.8	75.0
Hams Creek	0.02	0.02	0.01	0.01	0.03	0.18	0.03	0.01	0.13	0.42	33.4	31.5	31.8	36.0	36.6
Juniper Creek	0.03	0.03	0.04	0.04	0.06	0.68	0.27	0.29	0.38	1.05	38.1	38.9	45.9	45.1	50.2
Little Lynches River	0.12	0.04	0.03	0.03	0.04	0.89	0.82	0.55	0.54	2.07	72.3	72.0	71.8	59.5	52.9
Crooked Creek (DNR)	0.00	0.01	0.05	0.04	0.11	0.00	0.00	0.06	0.35	1.54	25.7	36.8	44.2	51.1	52.6
Juniper Creek (DNR)	0.06	0.02	0.02	0.03	0.06	0.00	0.57	0.16	0.41	1.04	57.3	52.1	49.1	45.3	49.3
Jefferies Creek (USGS)	0.19	0.17	0.15	0.17	0.19	3.50	9.02	8.30	3.33	5.92	41.3	43.4	41.0	70.3	71.0
Black Creek below Chesterfield	0.00	0.01	0.01	0.04	0.08	0.04	0.19	0.09	0.85	1.94	55.0	46.7	47.4	49.2	49.7
Crooked Creek	0.03	0.02	0.02	0.08	0.07	0.00	0.13	0.04	0.82	1.54	57.1	62.7	58.1	58.5	61.8
Black Creek near McBee	0.01	0.04	0.03	0.03	0.05	1.88	2.38	1.14	0.55	1.15	50.6	52.2	52.1	45.5	44.4
Thompson Creek	0.03	0.06	0.06	0.04	0.05	0.01	0.04	0.86	0.27	0.66	58.3	62.6	62.9	64.6	64.7
Lynches River at Hwy 1	0.00	0.03	0.03	0.04	0.05	0.00	0.07	0.12	0.32	0.76	64.6	65.0	63.1	57.7	54.4
Black Creek near Quinby	0.13	0.04	0.04	0.11	0.12	1.38	0.30	0.15	1.75	2.22	40.0	48.5	47.3	61.9	59.2
Lynches River near Bishopville	0.03	0.01	0.00	0.03	0.05	0.13	0.03	0.01	0.31	0.75	61.4	58.6	56.9	57.5	53.2

Table C1-2 – Land use summary by watershed. Titles of *200*, *1000*, *2000*, and *Ent* represent the distance (in meters) from the sampled point within the buffer, while Catchment refers to the entire watershed.

Site Name (Association)	% Agriculture					% Forest					% Wetland				
	200	1000	2000	Ent	Catchment	200	1000	2000	Ent	Catchment	200	1000	2000	Ent	Catchment
Huckleberry Branch	0.0	0.3	3.5	37.0	5.2	48.5	46.1	29.7	55.4	63.6	33.3	49.1	69.1	29.5	6.9
Little Fork Creek	0.0	0.0	1.6	11.6	15.1	0.0	22.6	15.3	37.6	27.0	100	72.3	60.5	37.7	19.9
Jefferies Creek (DNR)	0.0	50.2	57.9	52.8	30.7	0.0	1.1	7.1	15.5	17.1	97.6	45.2	31.5	21.7	20.4
Hams Creek	0.0	0.0	0.0	1.1	15.4	13.6	39.5	38.8	44.9	52.5	68.2	56.0	54.5	37.0	14.5
Juniper Creek	6.7	1.4	10.7	7.3	37.2	20.0	31.9	41.1	70.2	62.8	60.0	44.8	37.6	11.6	5.0
Little Lynches River	0.0	9.0	15.8	8.1	12.4	0.0	37.0	14.2	77.3	69.2	58.2	64.5	62.3	6.2	2.2
Crooked Creek (DNR)	0.0	4.9	16.4	9.7	9.9	18.9	13.4	11.7	12.2	17.1	59.5	55.1	67.7	24.8	14.7
Juniper Creek (DNR)	0.0	0.0	0.1	6.8	32.3	13.3	15.6	24.3	42.1	52.7	73.3	70.5	57.0	38.8	14.3
Jefferies Creek (USGS)	0.0	0.0	0.5	44.2	15.8	0.0	23.2	29.8	63.4	58.4	78.2	47.9	44.3	11.8	6.1
Black Creek below Chesterfield	0.0	0.0	0.6	8.0	13.4	9.2	14.2	19.7	66.9	63.5	78.2	59.3	49.9	8.3	3.9
Crooked Creek	0.0	5.3	6.1	24.4	17.3	0.0	24.7	42.2	46.8	40.6	100	71.0	53.7	21.5	9.4
Black Creek near McBee	0.0	6.2	2.9	5.2	13.8	3.7	27.2	38.0	48.6	51.3	88.9	47.2	46.2	27.8	11.1
Thompson Creek	12.6	23.8	16.8	11.7	40.0	33.3	14.9	16.2	25.5	33.7	43.8	74.5	71.4	28.2	15.3
Lynches River at Hwy 1	0.0	9.7	7.0	11.8	50.0	54.9	80.7	63.4	60.0	52.0	15.7	13.8	5.0	7.2	3.5
Black Creek near Quinby	0.0	3.5	8.8	31.0	7.5	23.8	6.5	6.6	13.7	16.5	31.0	50.9	53.3	26.2	20.8
Lynches River near Bishopville	0.0	0.0	0.0	10.9	15.1	0.0	7.6	4.5	60.9	56.3	93.5	90.4	91.4	15.9	8.8

APPENDIX C2: Channel Geometry and Profile

Note: The blue horizontal line in each figure followed by and “a” represents the depth that was determined to be bankfull, or when the water begins to spread out onto the flood plain. This was determined using a mixture of cross sectional geometry as well as indications of scour and woody vegetation on the banks. Also, please note that due to the size distribution of the sample sites, it was nearly impossible to get an accurate slope survey of the larger rivers with a manual survey. To remedy this, two open areas on each of the three largest rivers were found and the elevation was determined using RTK GPS. The water slope was then determined between these two points.

Huckleberry Branch

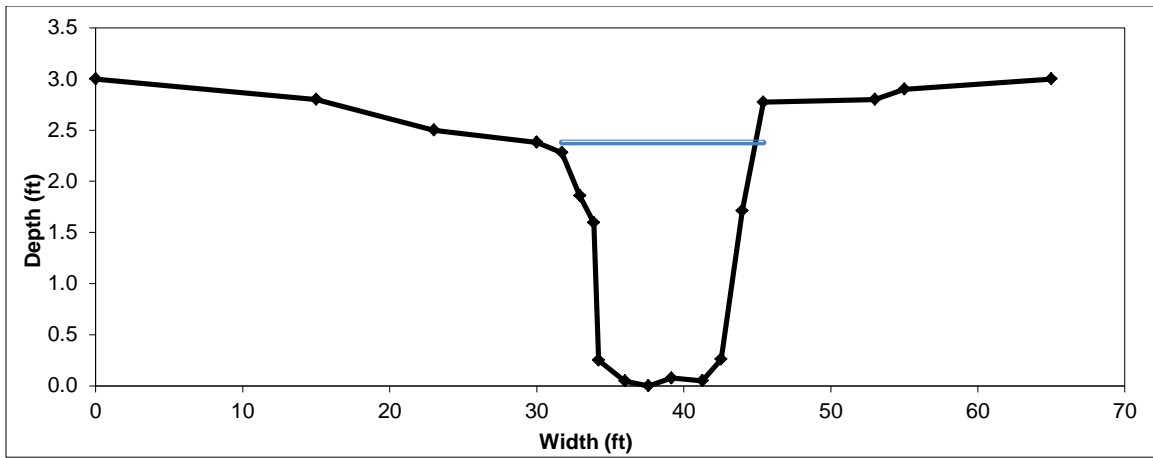


Figure C2-1a: Cross-sectional from Huckleberry Branch. The horizontal blue line represents the projected bankfull based upon channel geometry and in-field observations.

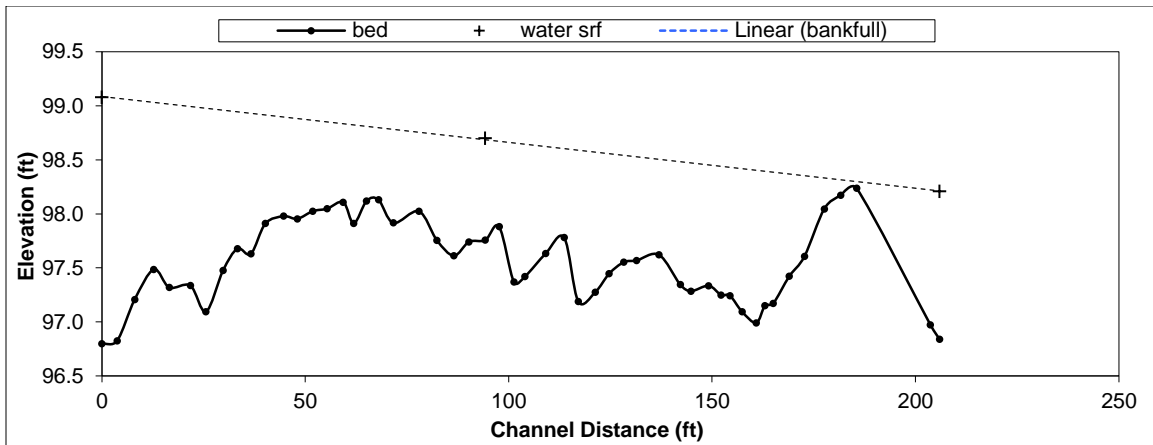


Figure C2-1b: Profile data from Huckleberry Branch. The “+” marks represent the measured water level and the dotted line represents the interpolated water slope. The points on the bed profile are measured values and the solid line is the interpolated bed value.

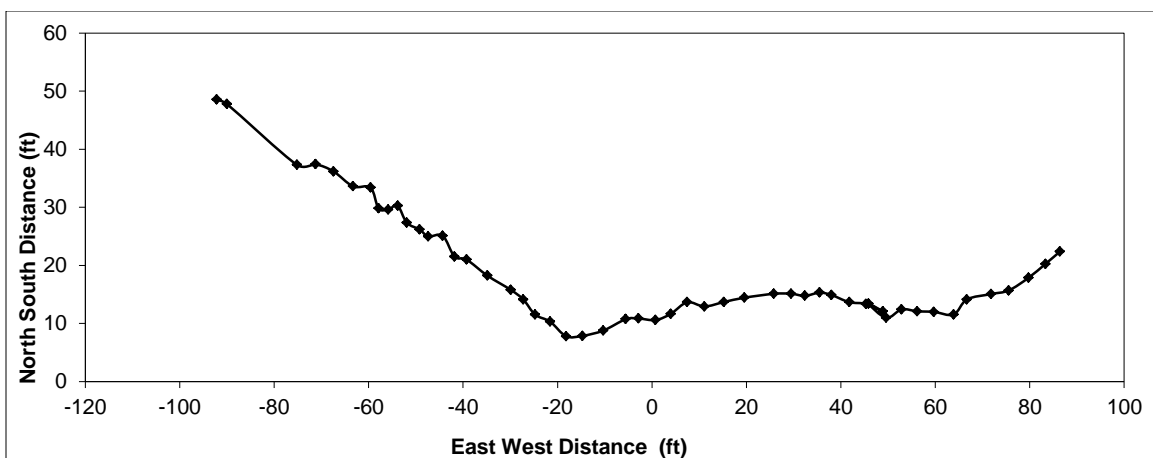


Figure C2-1c: Plan view of the surveyed section of the stream from the profile data of Huckleberry Branch.

Little Fork Creek (USGS)

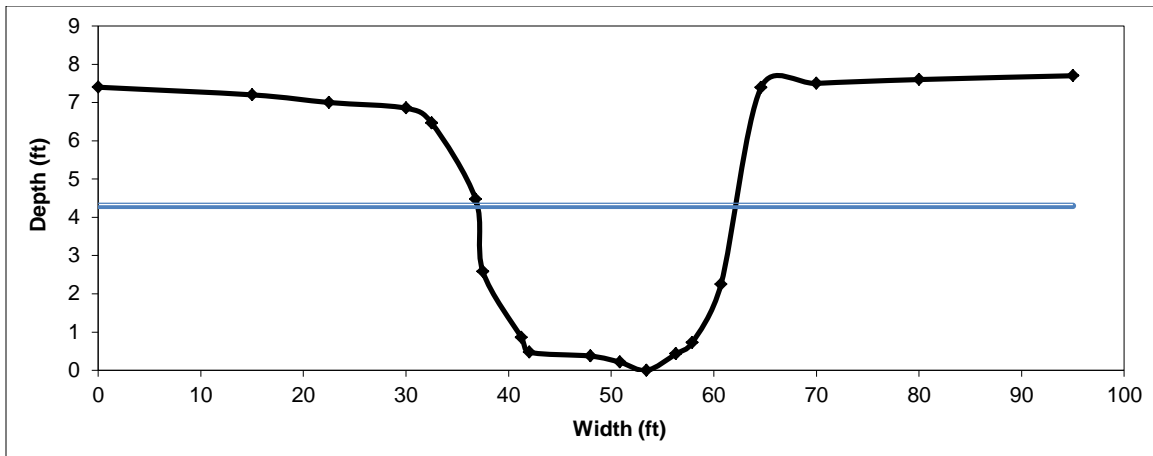


Figure C2-2a: Cross-sectional from Little Fork Creek (USGS). The horizontal blue line represents the projected bankfull based upon channel geometry and in-field observations.

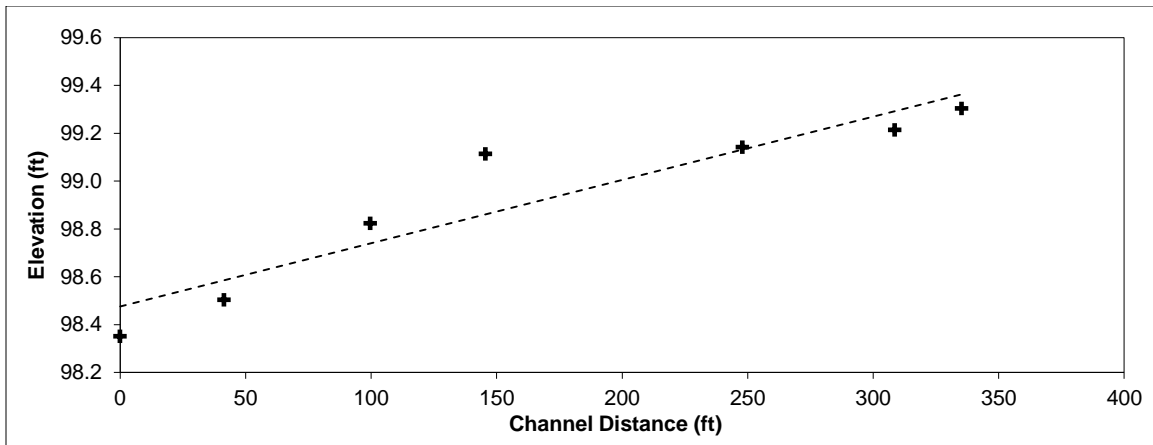


Figure C2-2b: Profile data from Little Fork Creek (USGS). The “+” marks represent the measured water level and the dotted line represents the interpolated water slope.

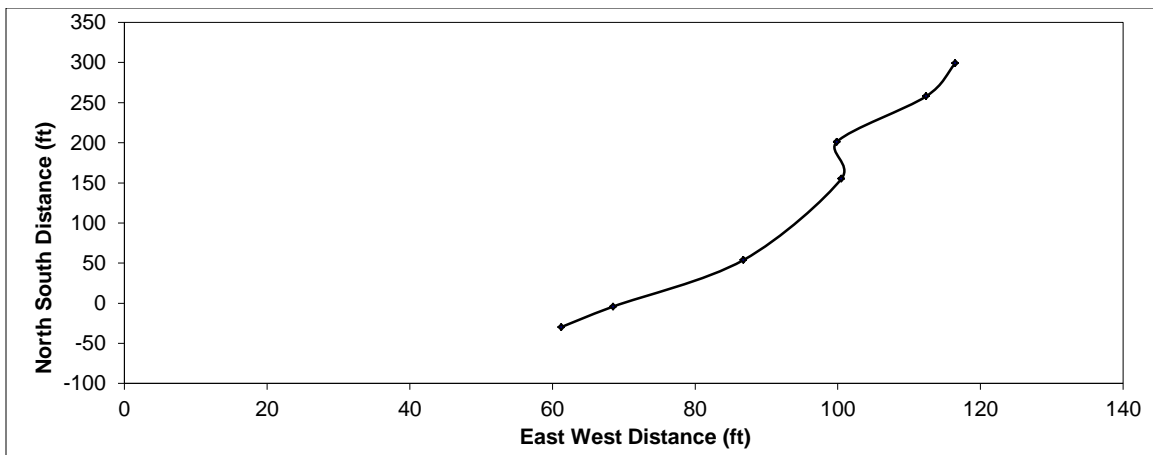


Figure C2-2c: Plan view of the surveyed section of the stream from the profile data of Little Fork Creek (USGS).

Hams Creek

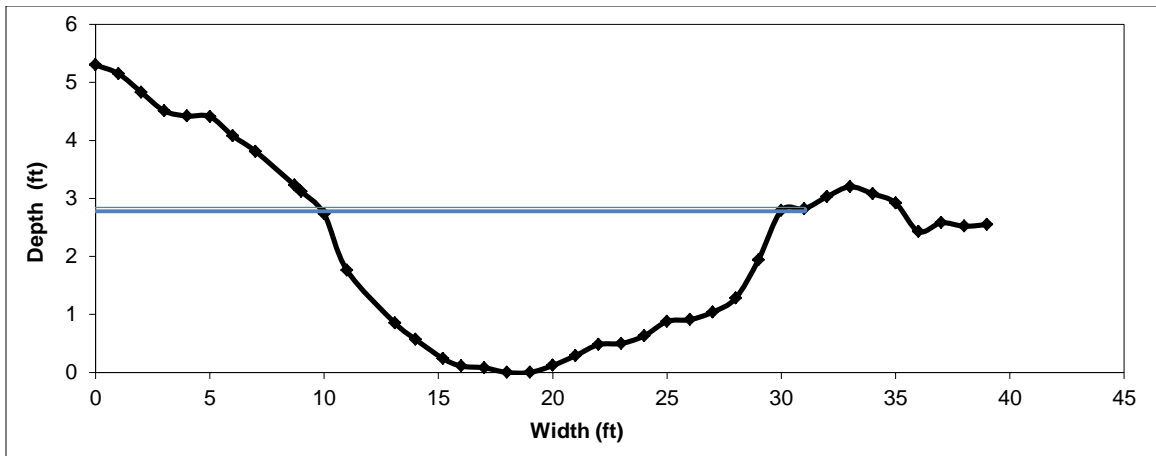


Figure C2-3a: Cross-sectional from Hams Creek. The horizontal blue line represents the projected bankfull based upon channel geometry and in-field observations.

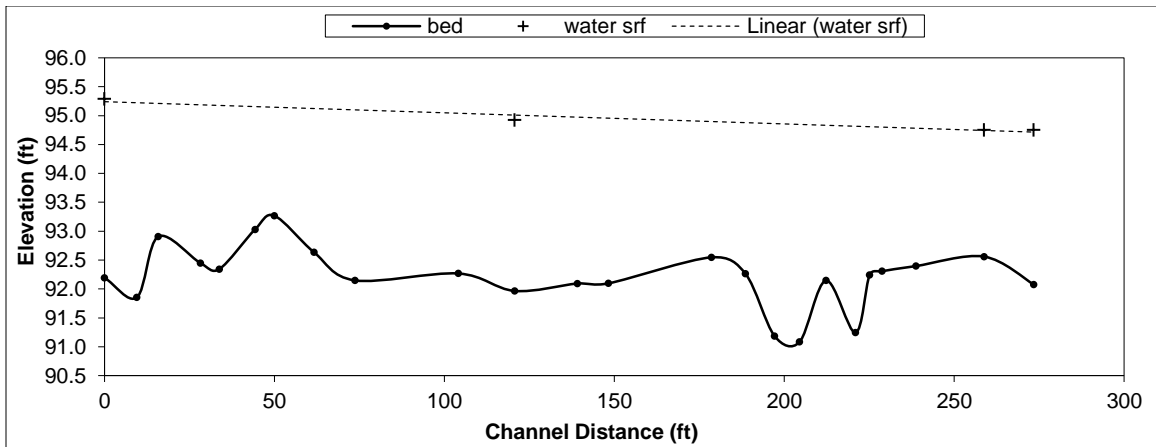


Figure C2-3b: Profile data from Hams Creek. The “+” marks represent the measured water level and the dotted line represents the interpolated water slope. The points on the bed profile are measured values and the solid line is the interpolated bed value.

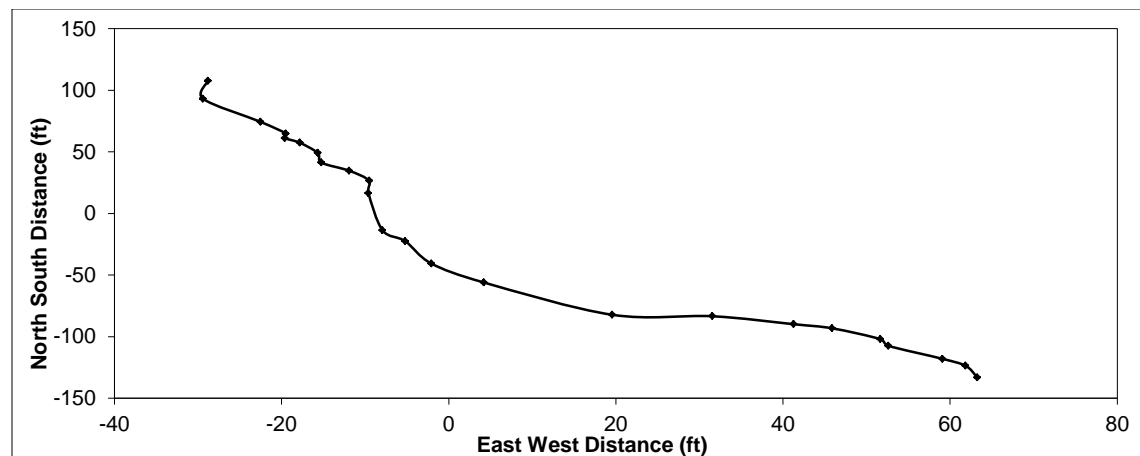


Figure C2-3c: Plan view of the surveyed section of the stream from the profile data of Hams Creek.

Juniper Creek

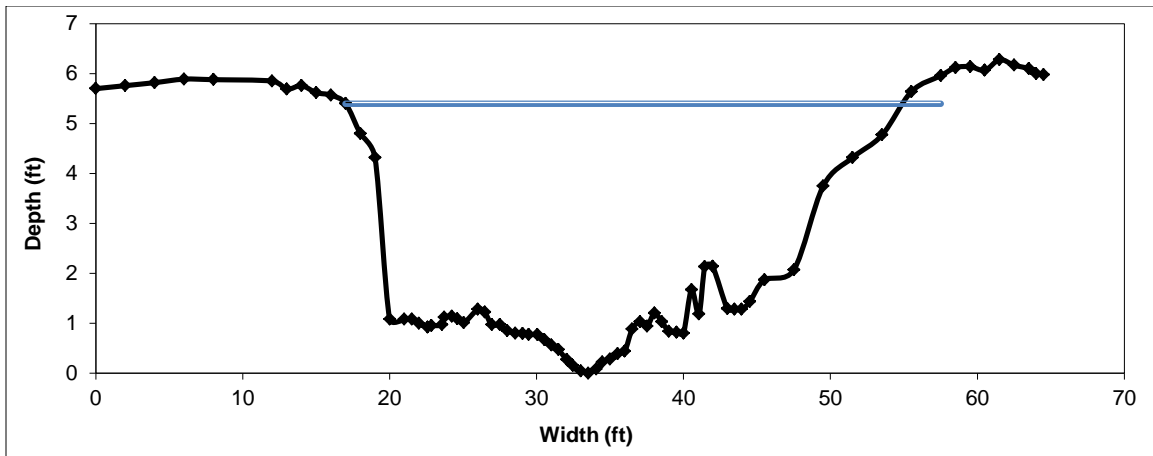


Figure C2-4a: Cross-sectional from Juniper Creek. The horizontal blue line represents the projected bankfull based upon channel geometry and in-field observations.

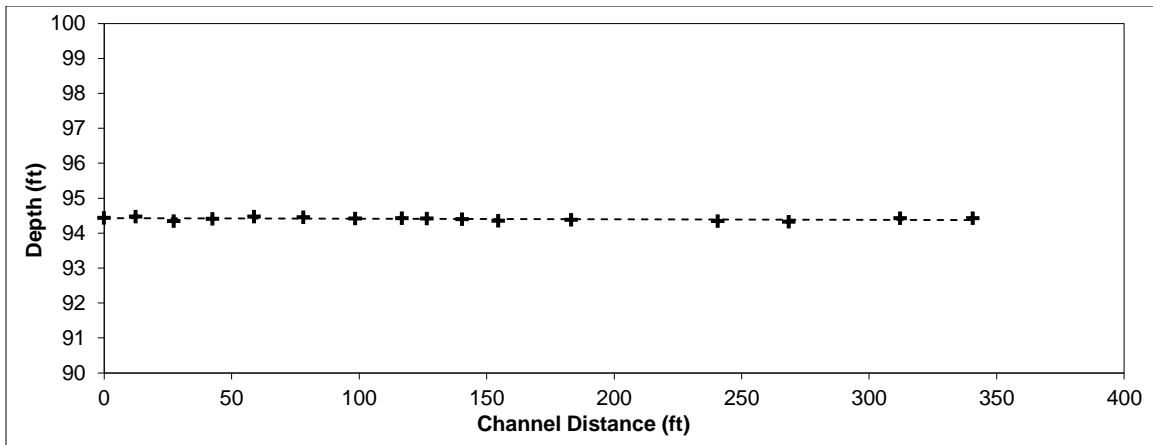


Figure C2-4b: Profile data from Juniper Creek. The “+” marks represent the measured water level and the dotted line represents the interpolated water slope.

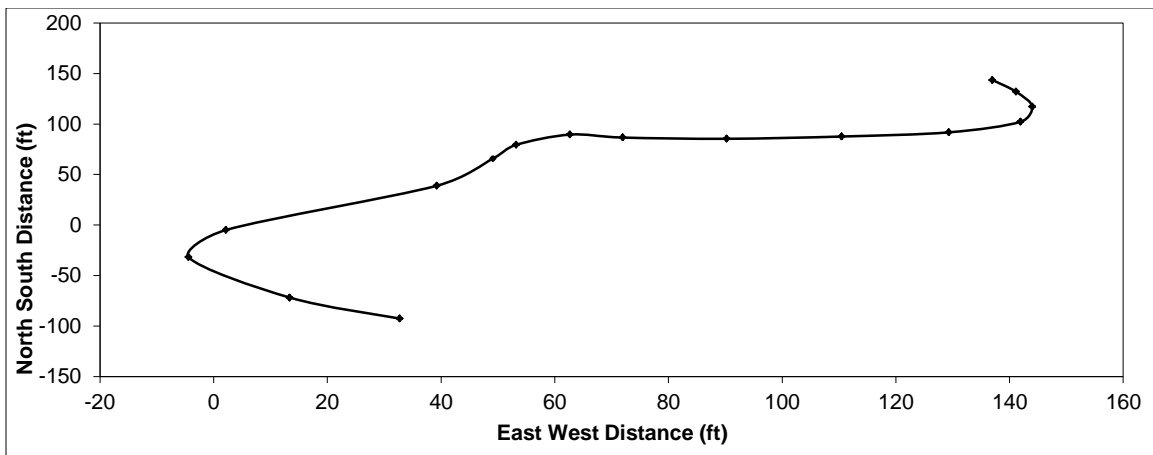


Figure C2-4c: Plan view of the surveyed section of the stream from the profile data of Juniper Creek.

Little Lynches River

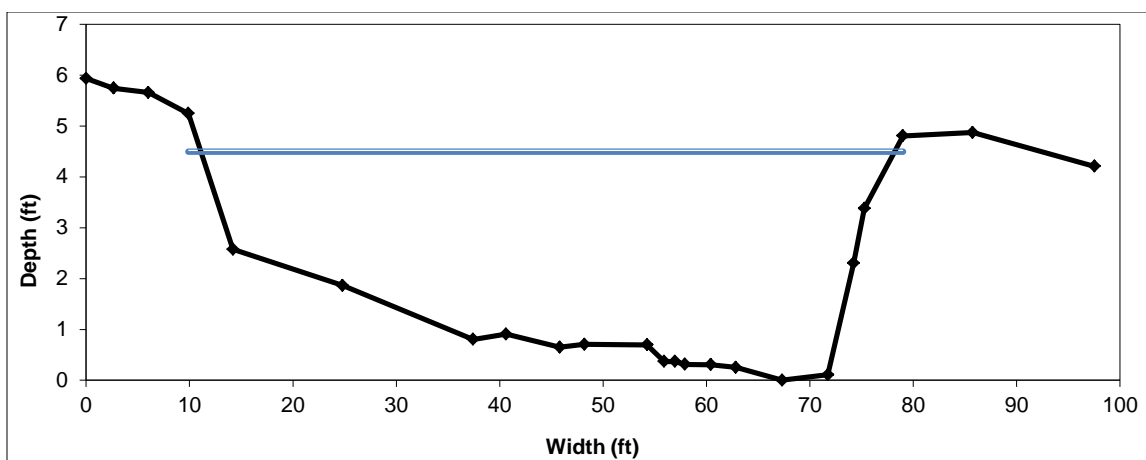


Figure C2-5a: Cross-sectional from Little Lynches River. The horizontal blue line represents the projected bankfull based upon channel geometry and in-field observations.

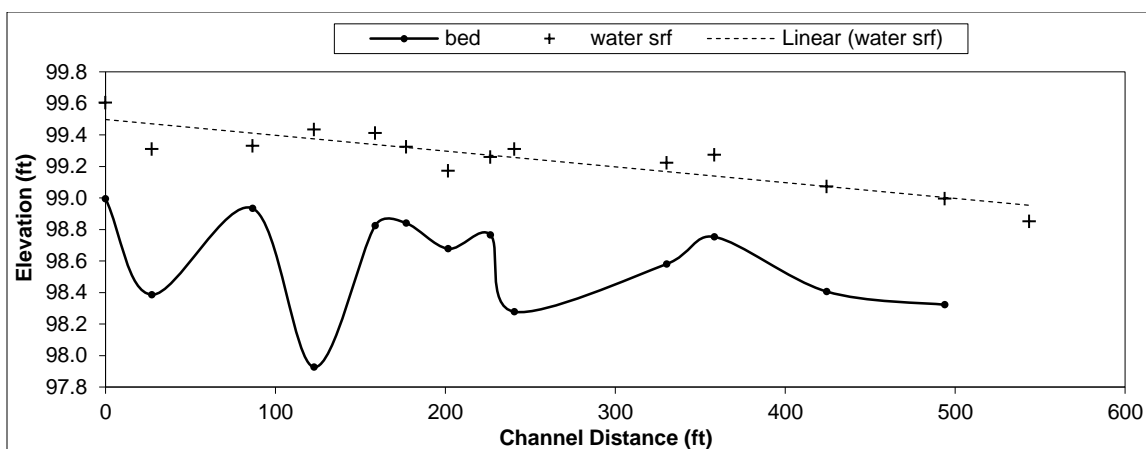


Figure C2-5b: Profile data from Little Lynches River. The “+” marks represent the measured water level and the dotted line represents the interpolated water slope. The points on the bed profile are measured values and the solid line is the interpolated bed value.

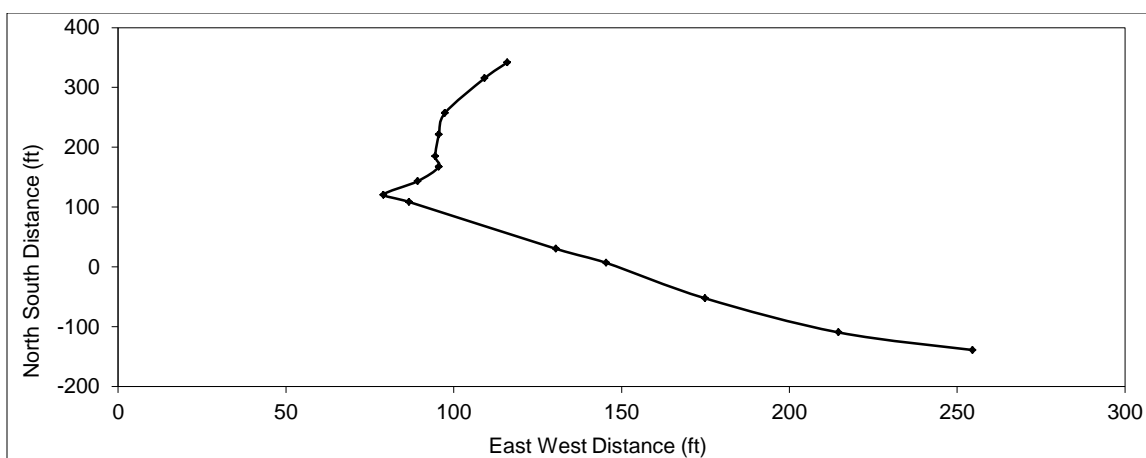


Figure C2-5c: Plan view of the surveyed section of the stream from the profile data of Little Lynches River.

Crooked Creek (DNR)

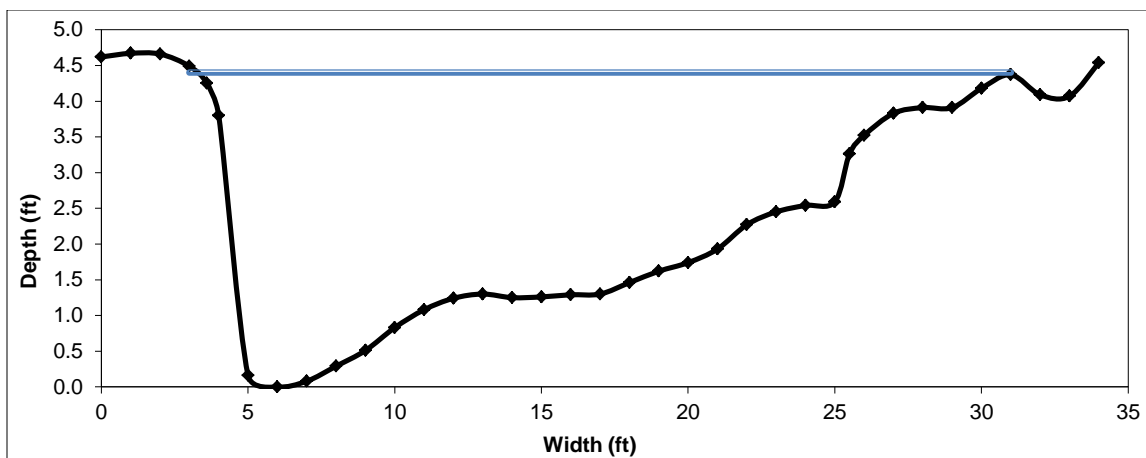


Figure C2-6a: Cross-sectional from Crooked Creek (DNR). The horizontal blue line represents the projected bankfull based upon channel geometry and in-field observations.

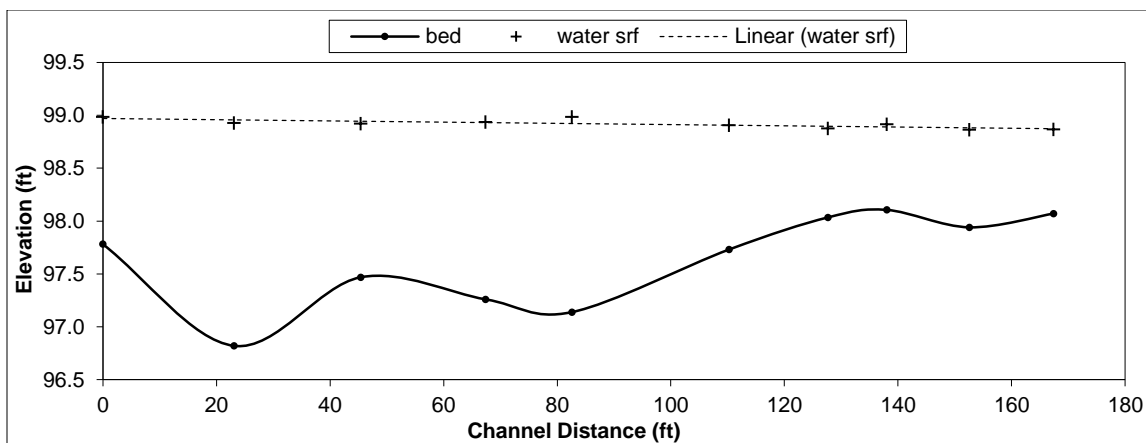


Figure C2-6b: Profile data from Crooked Creek (DNR). The “+” marks represent the measured water level and the dotted line represents the interpolated water slope. The points on the bed profile are measured values and the solid line is the interpolated bed value.

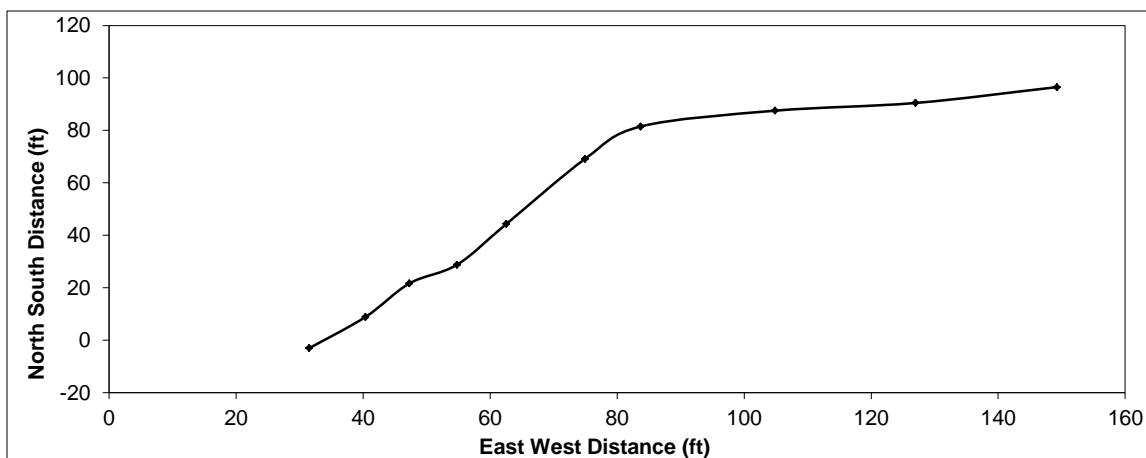


Figure C2-6c: Plan view of the surveyed section of the stream from the profile data of Crooked Creek (DNR).

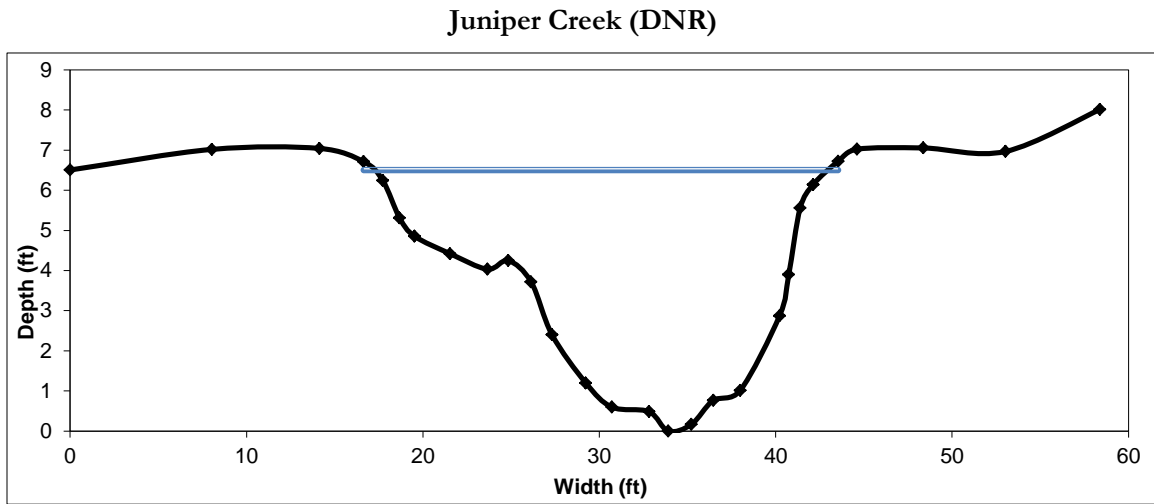


Figure C2-7a: Cross-sectional from Juniper Creek (DNR). The horizontal blue line represents the projected bankfull based upon channel geometry and in-field observations.

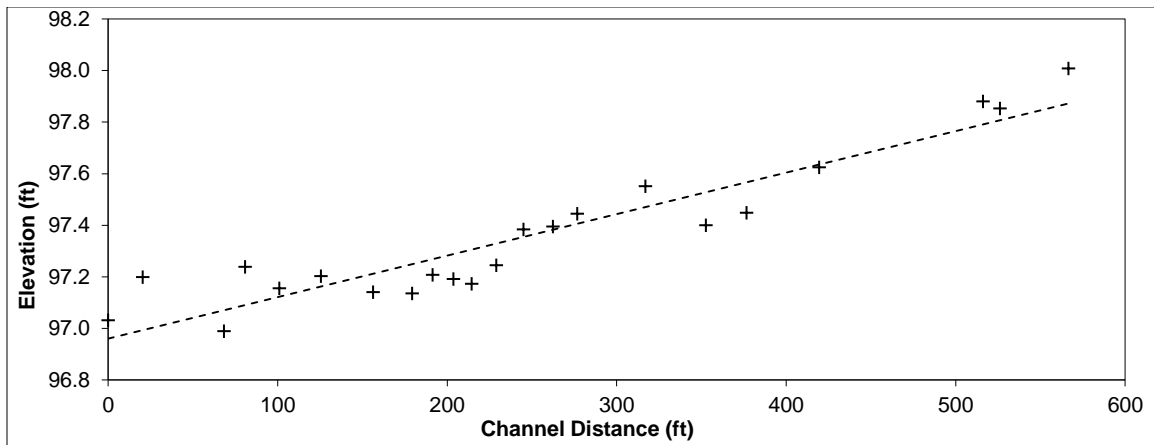


Figure C2-7b: Profile data from Juniper Creek (DNR). The “+” marks represent the measured water level and the dotted line represents the interpolated water slope.

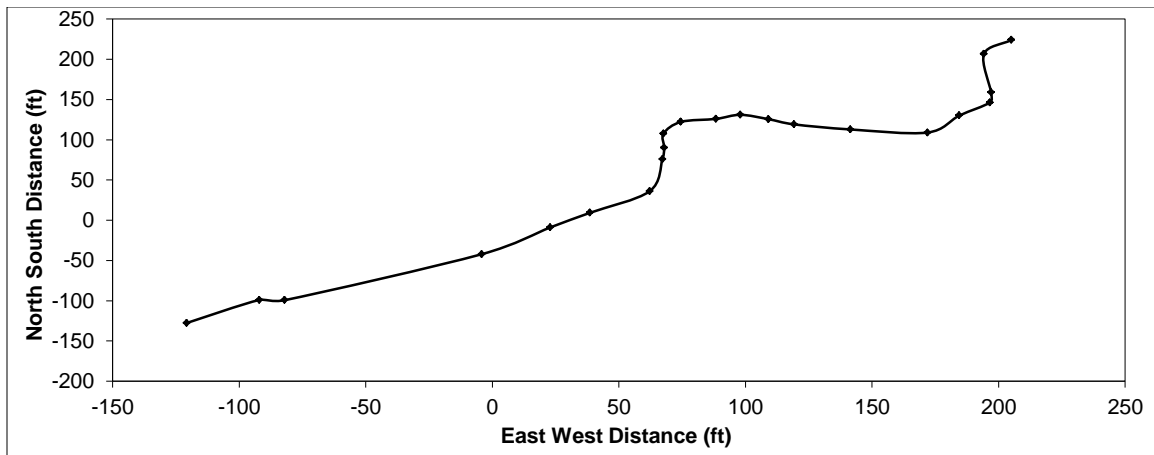


Figure C2-7c: Plan view of the surveyed section of the stream from the profile data of Juniper Creek (DNR).

Jeffries Creek (USGS)

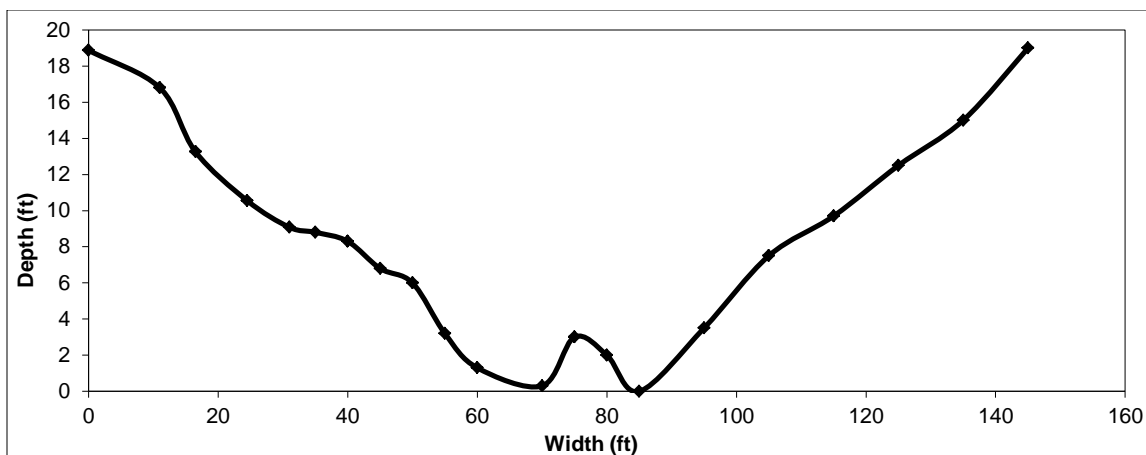


Figure C2-8a: Cross-sectional from Jeffries Creek (USGS). The horizontal blue line represents the projected bankfull based upon channel geometry and in-field observations.

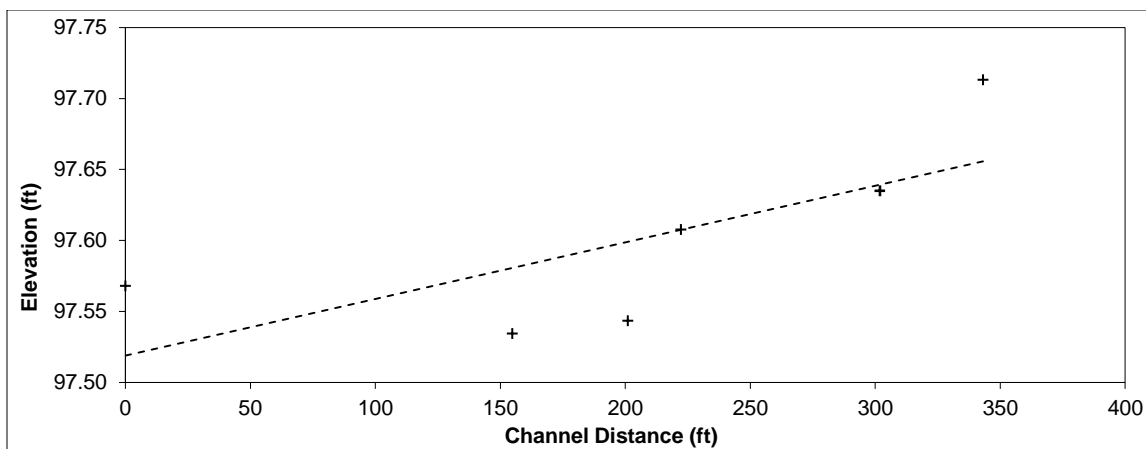


Figure C2-8b: Profile data from Jeffries Creek (USGS). The “+” marks represent the measured water level and the dotted line represents the interpolated water slope.

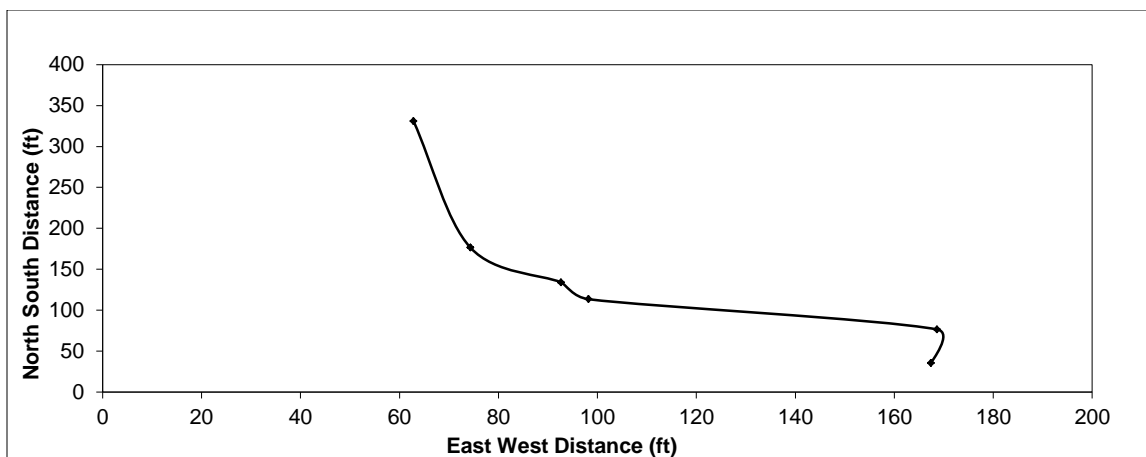


Figure C2-8c: Plan view of the surveyed section of the stream from the profile data of Jeffries Creek (USGS).

Black Creek below Chesterfield (USGS)

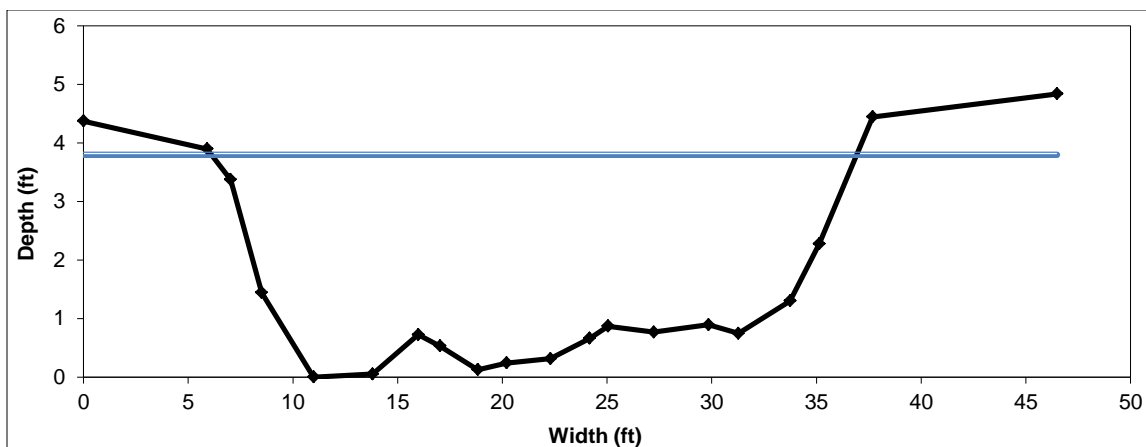


Figure C2-9a: Cross-sectional from Black Creek below Chesterfield (USGS). The horizontal blue line represents the projected bankfull based upon channel geometry and in-field observations.

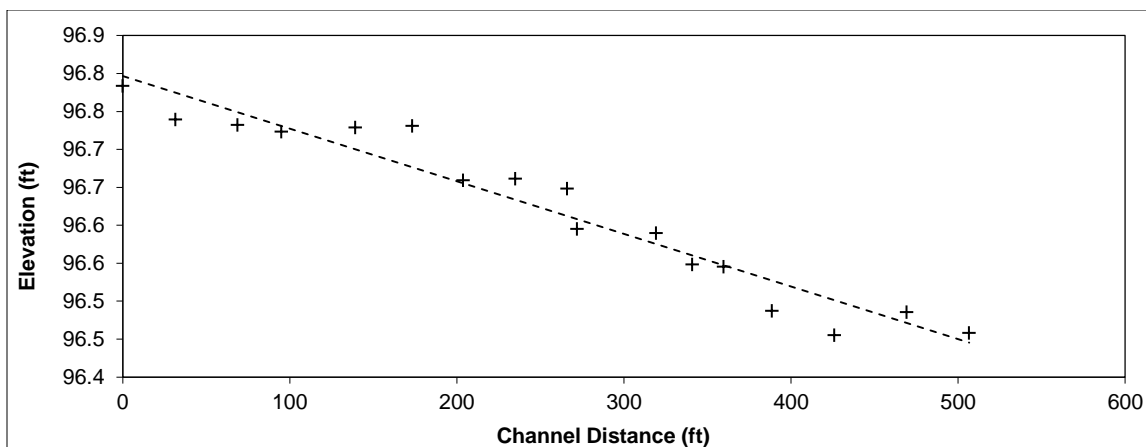


Figure C2-9b: Profile data from Black Creek below Chesterfield (USGS). The “+” marks represent the measured water level and the dotted line represents the interpolated water slope.

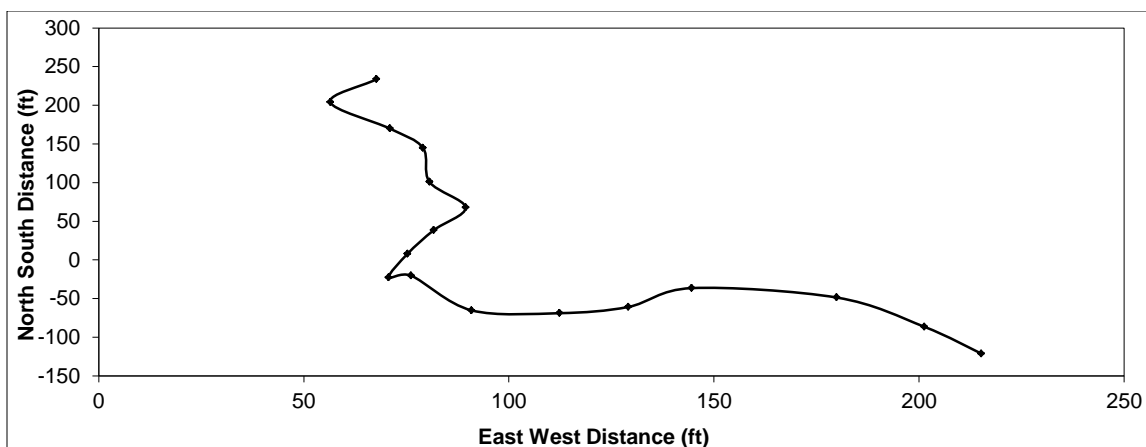


Figure C2-9c: Plan view of the surveyed section of the stream from the profile data of Black Creek below Chesterfield (USGS).

Crooked Creek

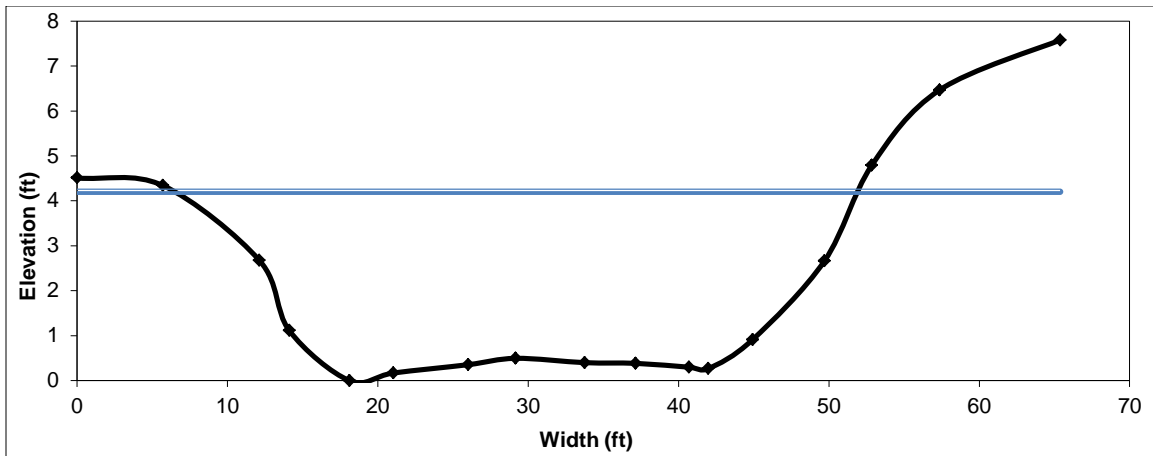


Figure C2-10a: Cross-sectional from Crooked Creek. The horizontal blue line represents the projected bankfull based upon channel geometry and in-field observations.

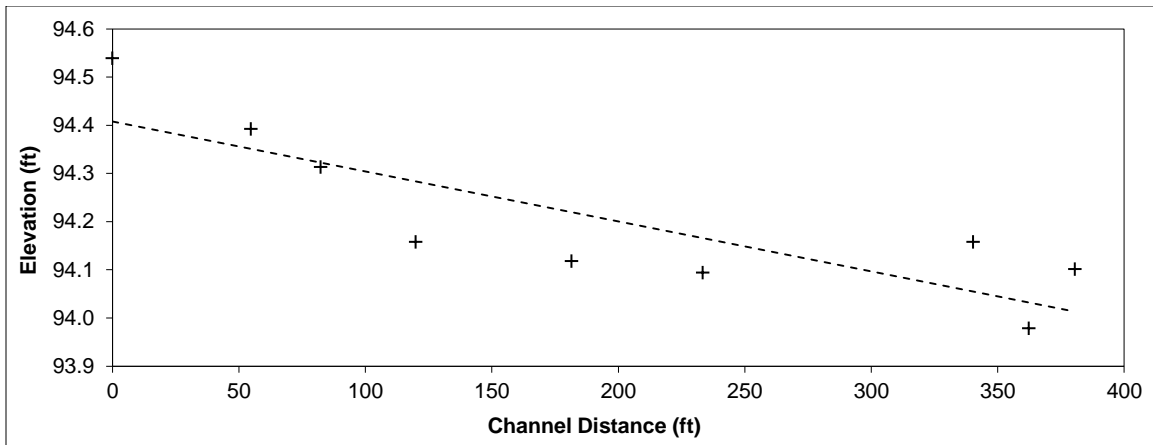


Figure C2-10b: Profile data from Crooked Creek. The “+” marks represent the measured water level and the dotted line represents the interpolated water slope.

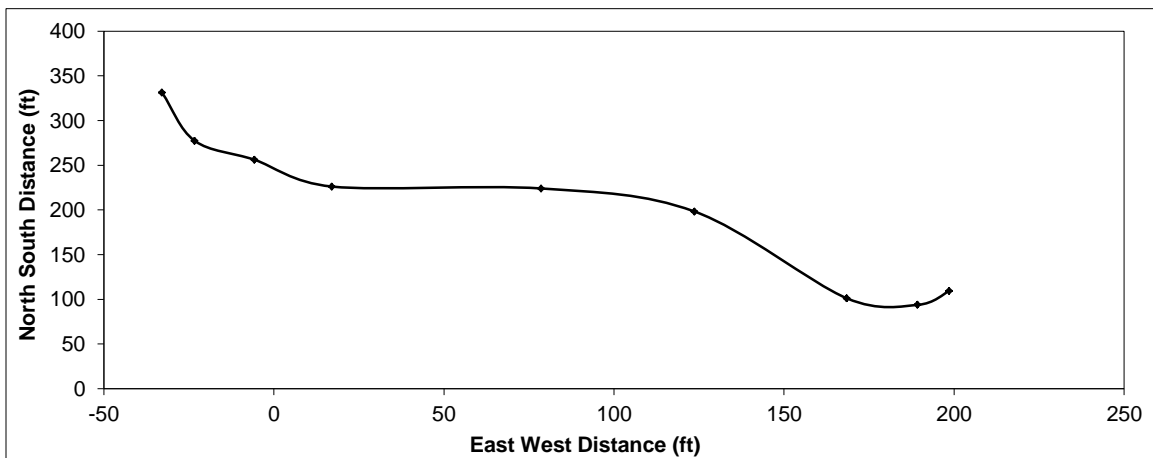


Figure C2-10c: Plan view of the surveyed section of the stream from the profile data of Crooked Creek.

Black Creek near McBee (USGS)

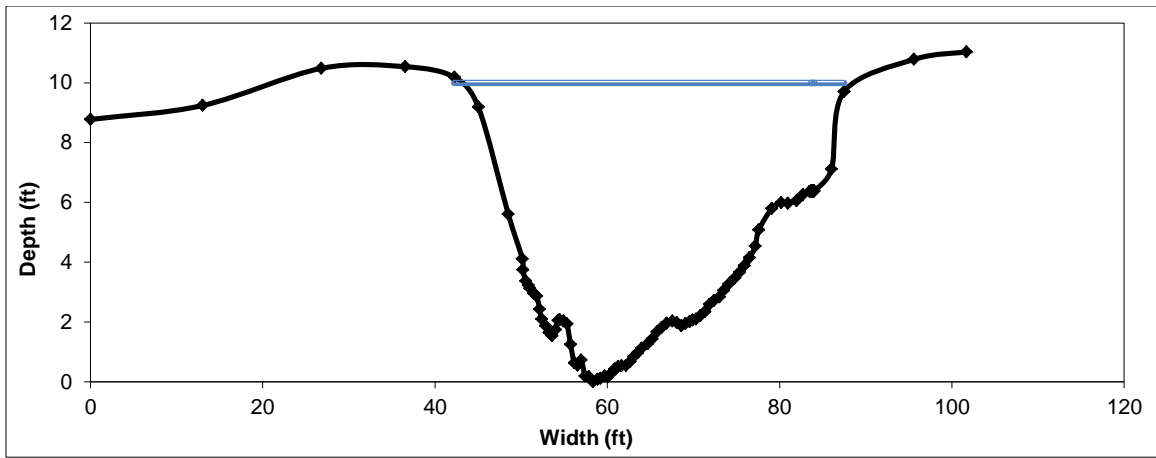


Figure C2-11a: Cross-sectional from Black Creek near McBee (USGS). The horizontal blue line represents the projected bankfull based upon channel geometry and in-field observations.

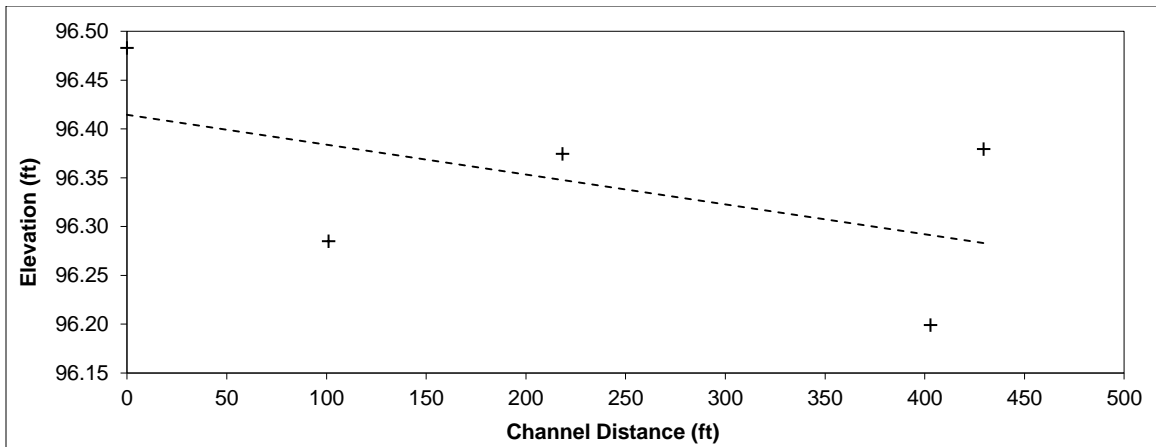


Figure C2-11b: Profile data from Black Creek near McBee (USGS). The “+” marks represent the measured water level and the dotted line represents the interpolated water slope.

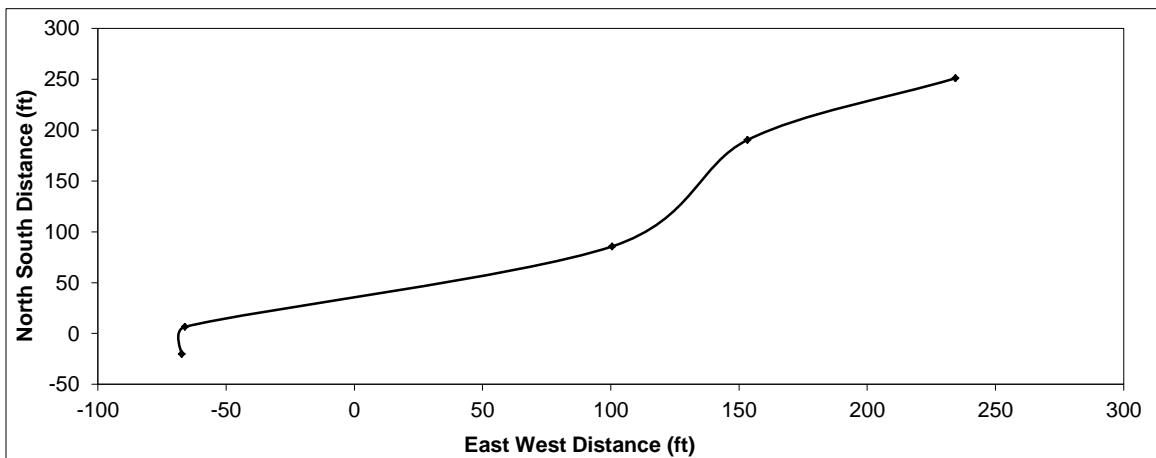


Figure C2-11c: Plan view of the surveyed section of the stream from the profile data of Black Creek near McBee (USGS).

Thompson Creek

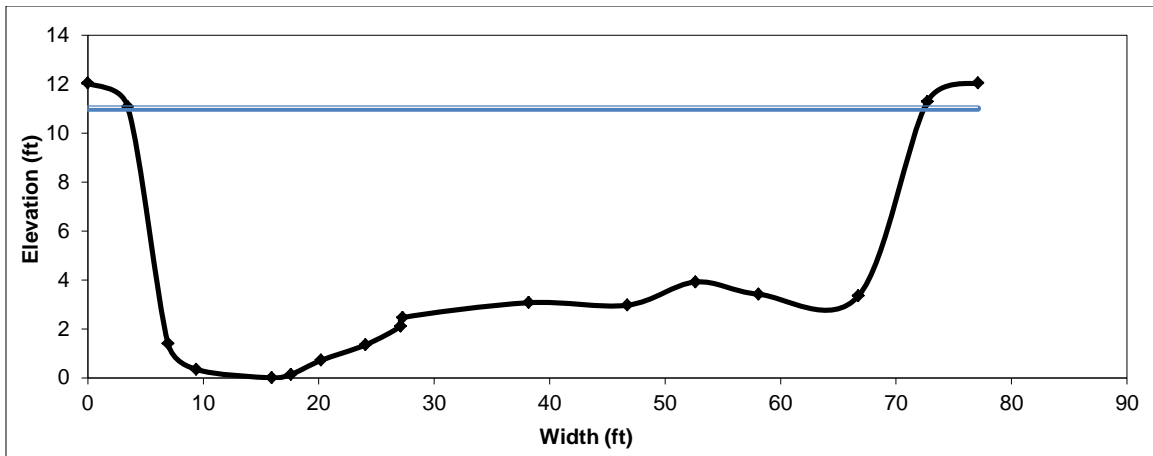


Figure C2-12a: Cross-sectional from Thompson Creek. The horizontal blue line represents the projected bankfull based upon channel geometry and in-field observations.

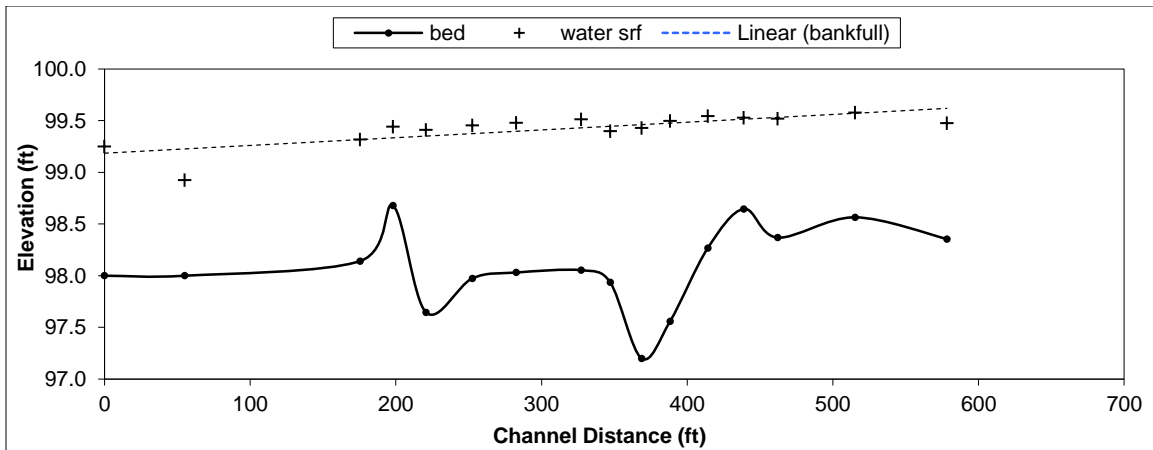


Figure C2-12b: Profile data from Thompson Creek. The “+” marks represent the measured water level and the dotted line represents the interpolated water slope.

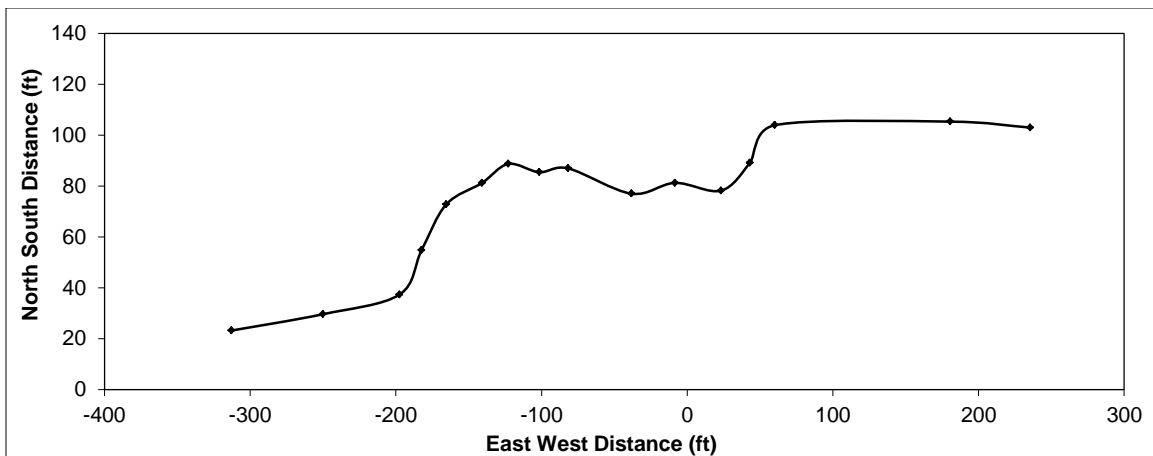


Figure C2-12c: Plan view of the surveyed section of the stream from the profile data of Thompson Creek.

Lynches River

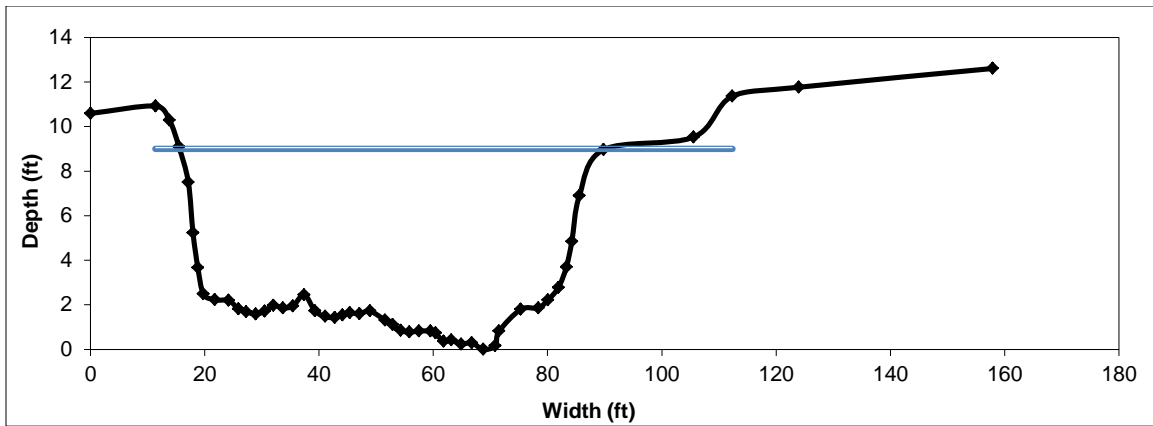


Figure C2-13a: Cross-sectional from Lynches River. The horizontal blue line represents the projected bankfull based upon channel geometry and in-field observations.

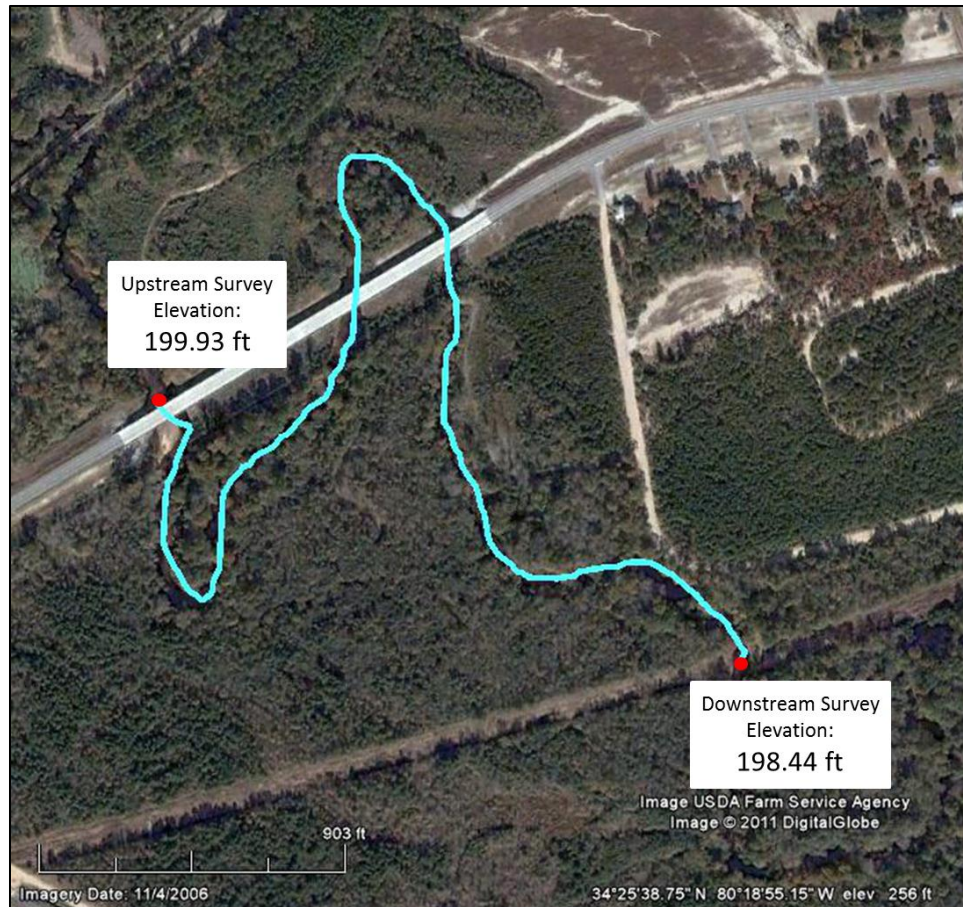


Figure C2-13b: Figure of slope taken RTK GPS on two points of Lynches River. The red dots represent the measurement points and the blue line represents the path of the river. Each point is labeled with a respective water elevation and the total travel distance for water within the stream between those points is 4,567 feet, yielding an average slope of 0.000326 ft/ft over the entire section.

Black Creek near Quinby (USGS)

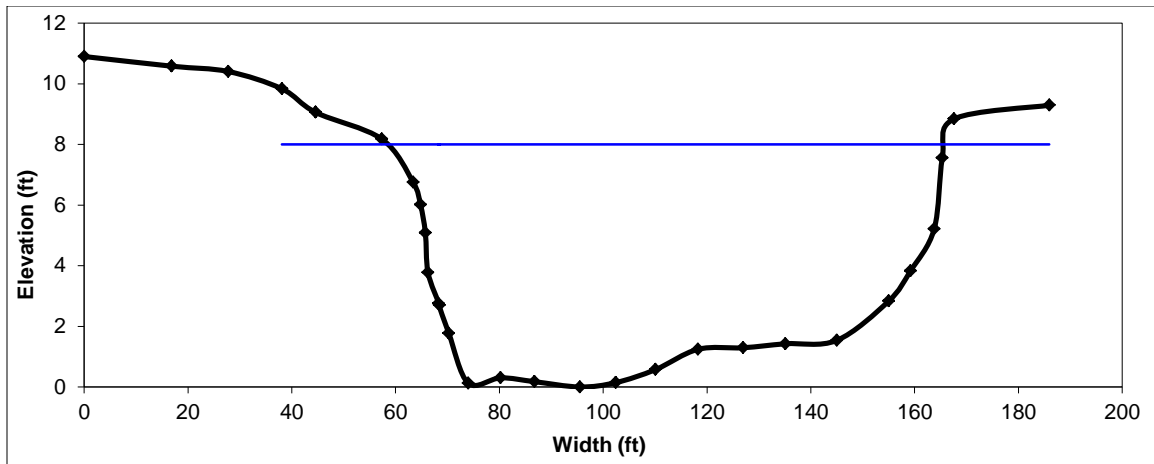


Figure C2-14a: Cross-sectional from Black Creek near Quinby (USGS). The horizontal blue line represents the projected bankfull based upon channel geometry and in-field observations.



Figure C2-14b: Figure of slope taken RTK GPS on two points of Black Creek near Quinby (USGS). The red dots represent the measurement points and the blue line represents the path of the river. Each point is labeled with a respective water elevation and the total travel distance for water within the stream between those points is 4,479 feet, yielding an average slope of 0.00141 ft/ft over the entire section.

Lynches River near Bishopville

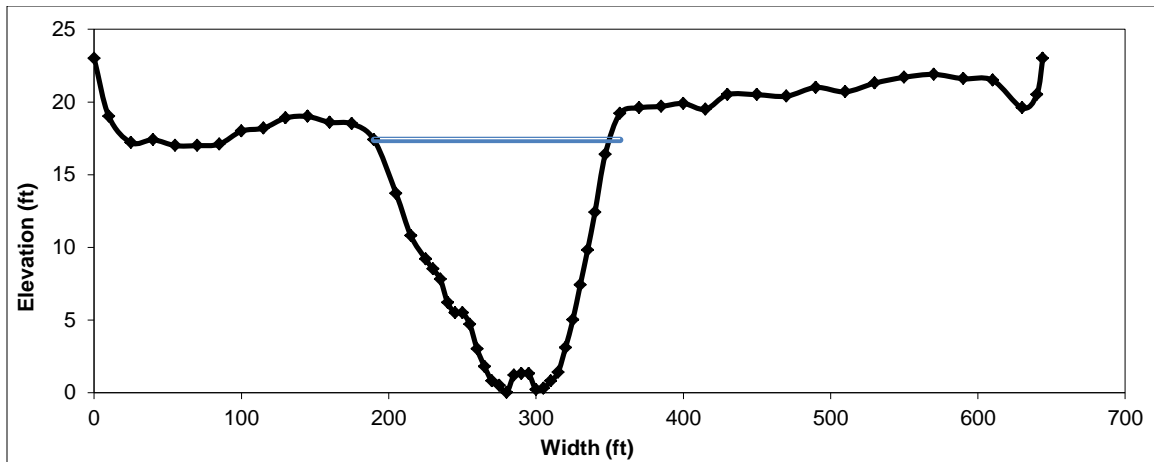


Figure C2-15a: Cross-sectional from Lynches River near Bishopville (USGS). The horizontal blue line represents the projected bankfull based upon channel geometry and in-field observations.

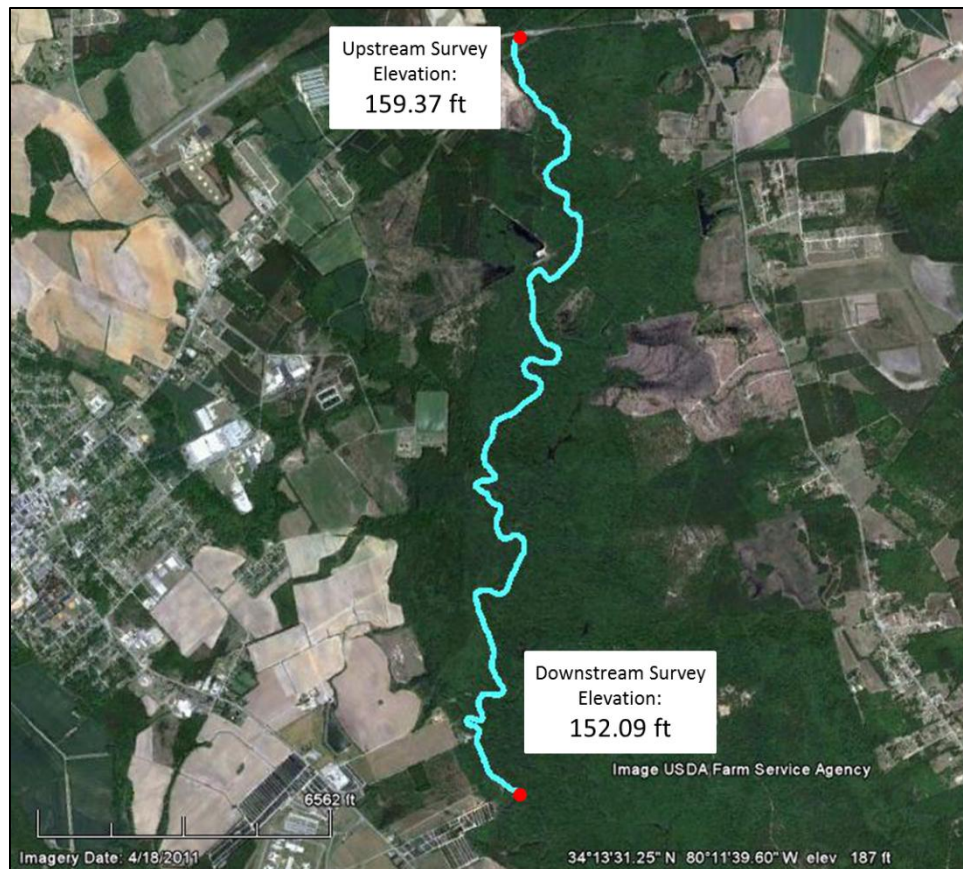


Figure C2-15b: Figure of slope taken RTK GPS on two points of Lynches River near Bishopville (USGS). The red dots represent the measurement points and the blue line represents the path of the river. Each point is labeled with a respective water elevation and the total travel distance for water within the stream between those points is 24,794 feet, yielding an average slope of 0.000294 ft/ft over the entire section.

APPENDIX C3: Site Panoramas

Site Pictures: Panoramas and bankfull estimate.

Note: Due to limitations of a camera to convey three-dimensional representation of streams, the panoramic software to portray the 180 degree view (Hugin®), and the photographer's ability to accurately portray the stream, panoramas vary in size and shape. Also, some stream panoramas do not show all aspects of the stream; aspects that could only truly be assessed via a site visit. However, stream views were portrayed to the best of the photographer's ability.



Figure C2-1: Panoramic photo of Huckleberry Branch. Due to the size of this stream, it was difficult to get a decent panorama, although this may be more of a function of photographic prowess than stream size. In either case, the bankfull was verified further down stream in dense underbrush, where no picture could be taken.



Figure C2-2: Panoramic photo of Little Fork Creek (USGS). The red line and arrows signify the level perceived as bankfull in the field, matching bankfull in Figure C2-2a in Appendix C2.



Figure C2-3: Panoramic photo of Hams Creek. The red line and arrows signify the level perceived as bankfull in the field, matching bankfull in Figure B1-3a in Appendix C2.



Figure C2-4: Panoramic photo of Juniper Creek. The red line and arrows signify the level perceived as bankfull in the field, matching bankfull in Figure C2-4a in Appendix C2.



Figure C2-5: Panoramic photo of Little Lynches River. This picture was taken to include the Levelogger, but no clear indication of bankfull can be seen here. However, bankfull was verified on a point bar in the far right portion of the picture that goes out of view.



Figure C2-6: Panoramic photo of Crooked Creek (DNR). The red line and arrows signify the level perceived as bankfull in the field, matching bankfull in Figure C2-6a in Appendix C2.



Figure C2-7: Panoramic photo of Juniper Creek (DNR). The red line and arrows signify the level perceived as bankfull in the field, matching bankfull in Figure C2-7a in Appendix C2.



Figure C2-8: Panoramic photo of Jeffries Creek (USGS). No clear bankfull could be determined at this site due to downstream impoundment.



Figure C2-9: Panoramic photo of Black Creek below Chesterfield (USGS). The red line and arrows signify the level perceived as bankfull in the field, matching bankfull in Figure C2-9a in Appendix C2.



Figure C2-10: Panoramic photo of Crooked Creek. The red line and arrows signify the level perceived as bankfull in the field, matching bankfull in Figure C2-10a in Appendix C2.



Figure C2-11: Panoramic photo of Black Creek near McBee (USGS). The red line and arrows signify the level perceived as bankfull in the field, matching bankfull in Figure C2-11a in Appendix C2.



Figure C2-12: Panoramic photo of Thompson Creek. The red line and arrows signify the level perceived as bankfull in the field, matching bankfull in Figure C2-12a in Appendix C2.



Figure C2-13: Panoramic photo of Lynch River. The red line and arrows signify the level perceived as bankfull in the field, matching bankfull in Figure C2-13a in Appendix C2.



Figure C2-14: Panoramic photo of Black Creek near Quinby (USGS). The red line and arrows signify the level perceived as bankfull in the field, matching bankfull in Figure C2-14a in Appendix C2.



Figure C2-15: Panoramic photo of Lynches River near Bishopville (USGS). The red line and arrows signify the level perceived as bankfull in the field, matching bankfull in Figure C2-15a in Appendix C2.

APPENDIX C4: Stream Hydrographs

Flow records of all sites with corresponding precipitation records of the closest available rain gauge.

Note: Some sites have *estimated flow rate* and *estimated data points* marked as dotted lines and circular data points in the graph. These are periods that the flow level exceeded that which was included in the stream survey and so can only be speculated. In most cases, these levels only exceeded the level of the survey by a matter of inches, and thus the assumption was that resistance to flow was enough to maintain an accurate volume of flow across the floodplain in comparison to the main channel. The dotted lines, representing *estimated flow* in the charts is there for continuity, while the *estimated data points* are estimated daily flow data derived from a mixture of Levellogger data, cross section data, measured flow data, and profile data. This estimate was necessary for the calculation of both Richards-Baker flashiness and estimated bed load. Precipitation is also included in the flow records. All flow records except those at Black Creek below Chesterfield, Lynches River near Bishopville, and Black Creek near Quinby, are estimated daily precipitation values based upon surrounding historical data from the cities of Cheraw, Florence, and Bennettsville.

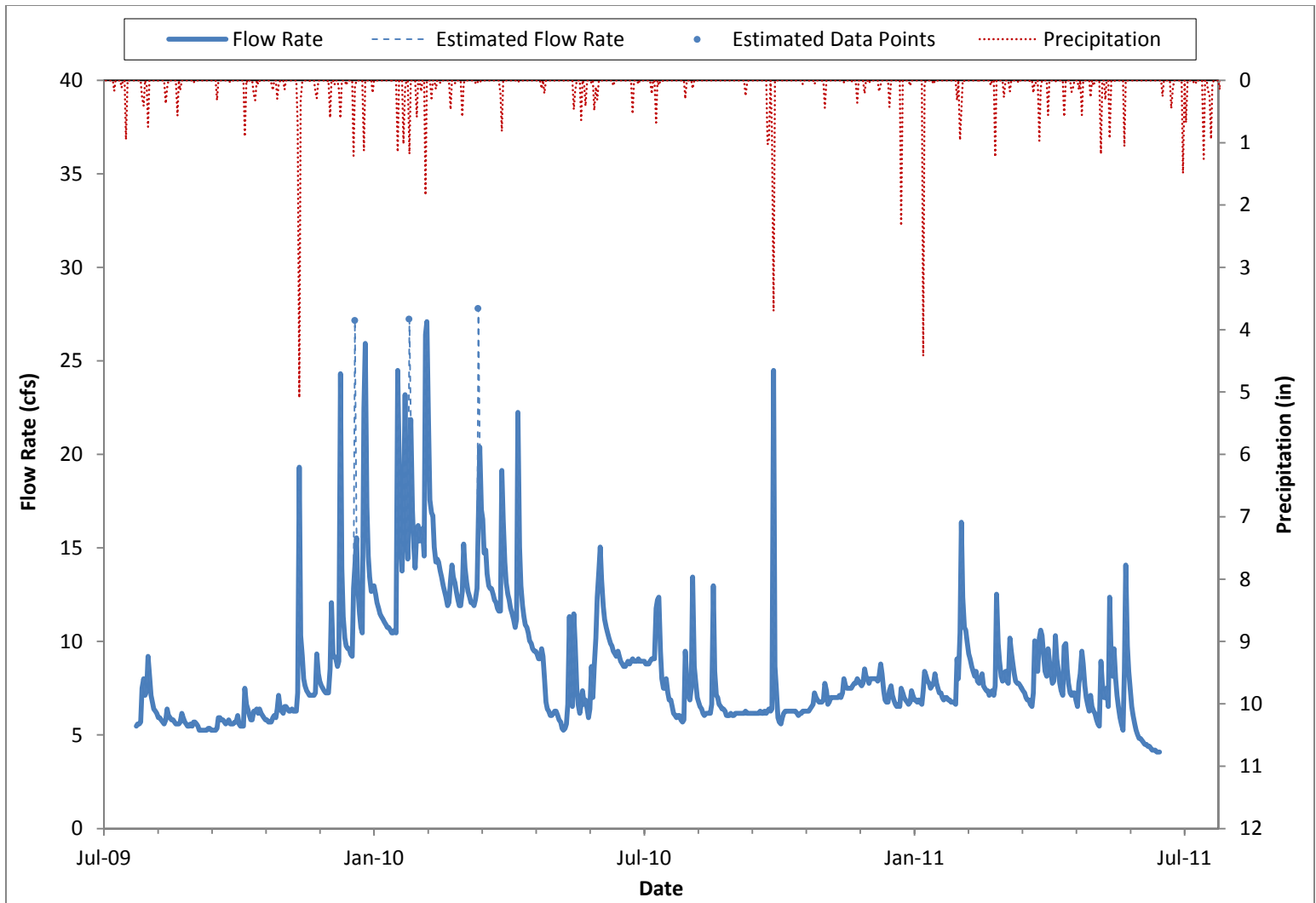


Figure C6-1: Huckleberry Branch flow rate and precipitation record.

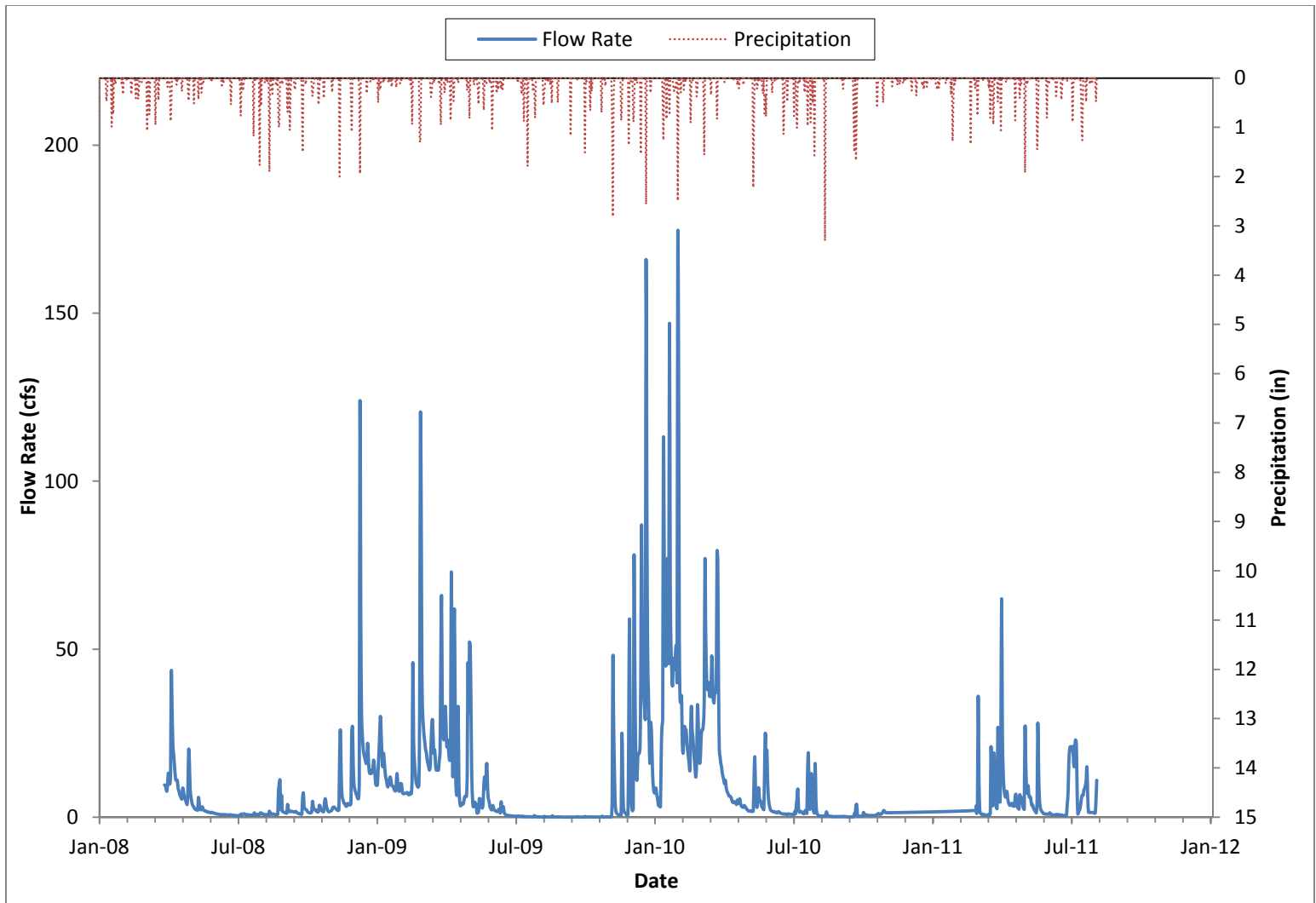


Figure C6-2: Little Fork Creek (USGS) flow rate and precipitation record.

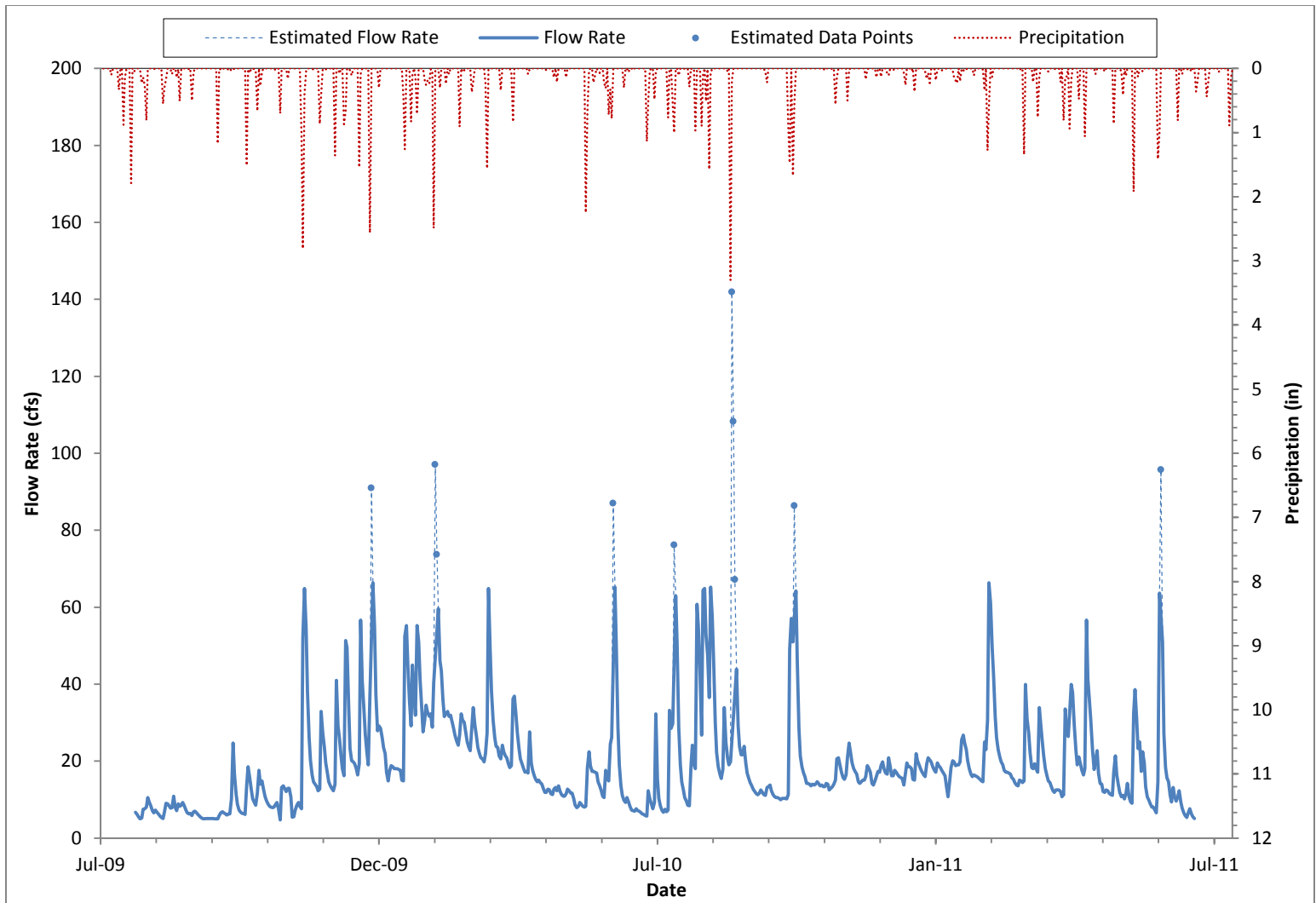


Figure C6-3: Hams Creek (DNR) flow rate and precipitation record.

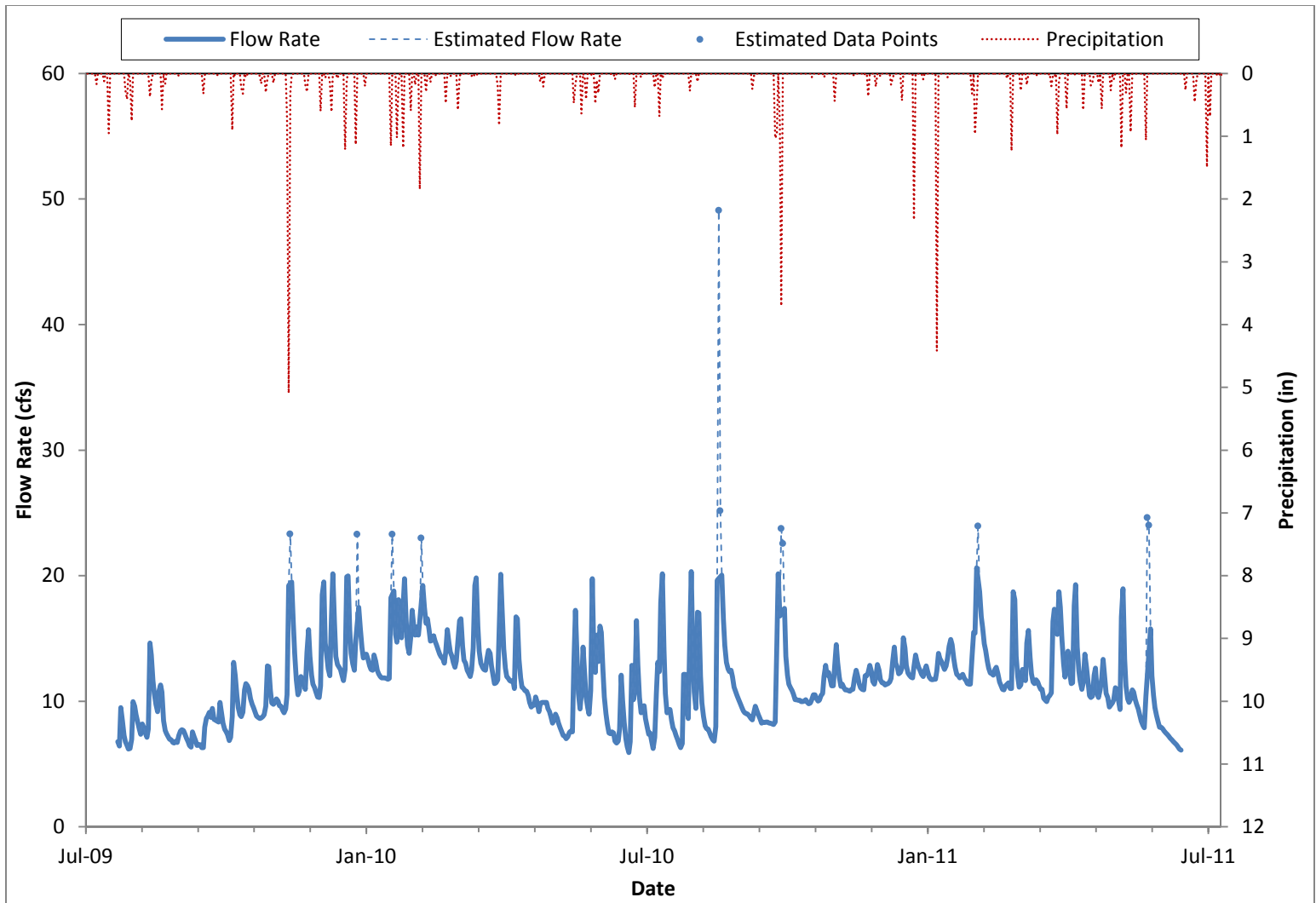


Figure C6-4: Juniper Creek flow rate and precipitation record.

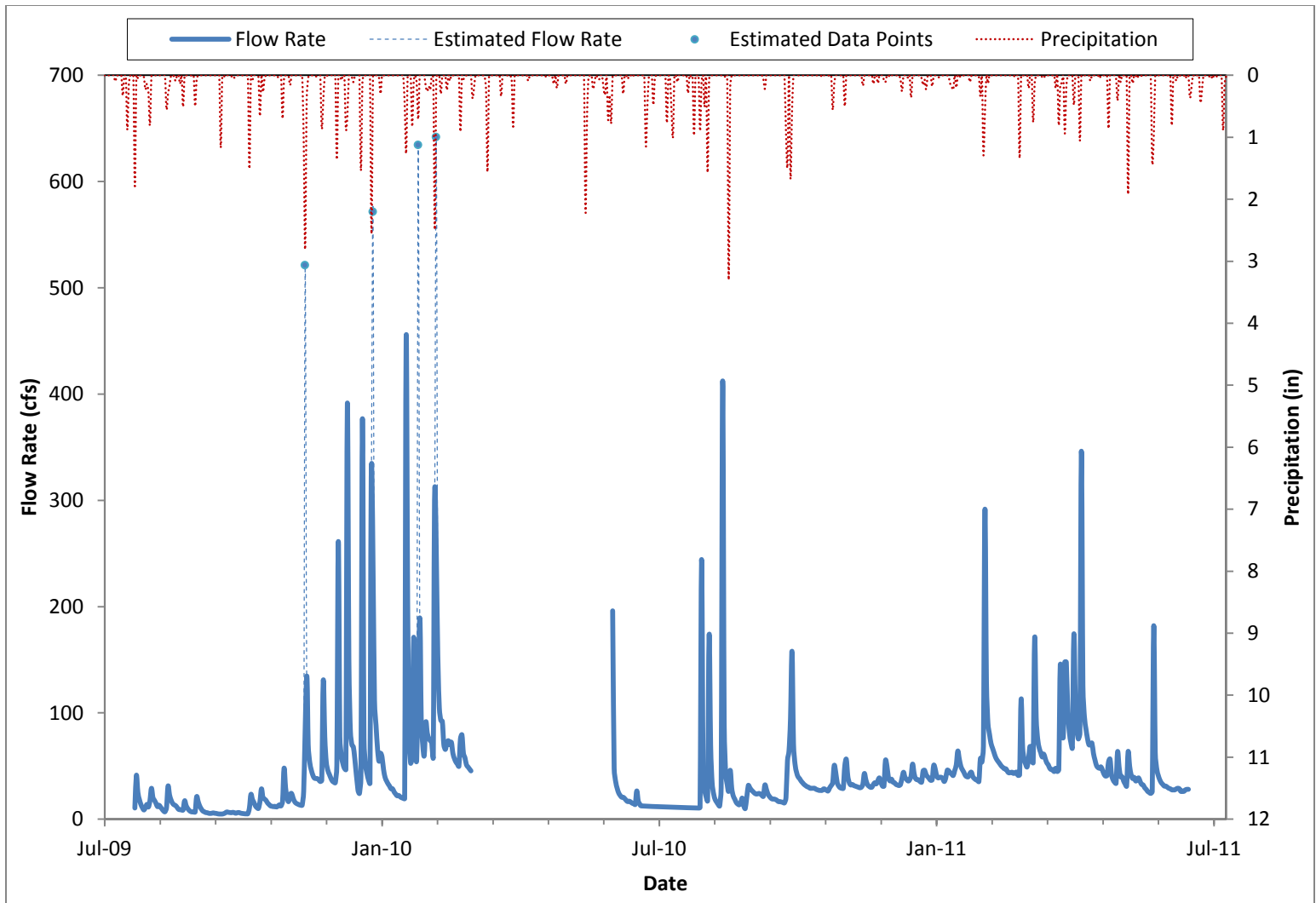


Figure C6-5: Little Lynches River (DNR) flow rate and precipitation record.

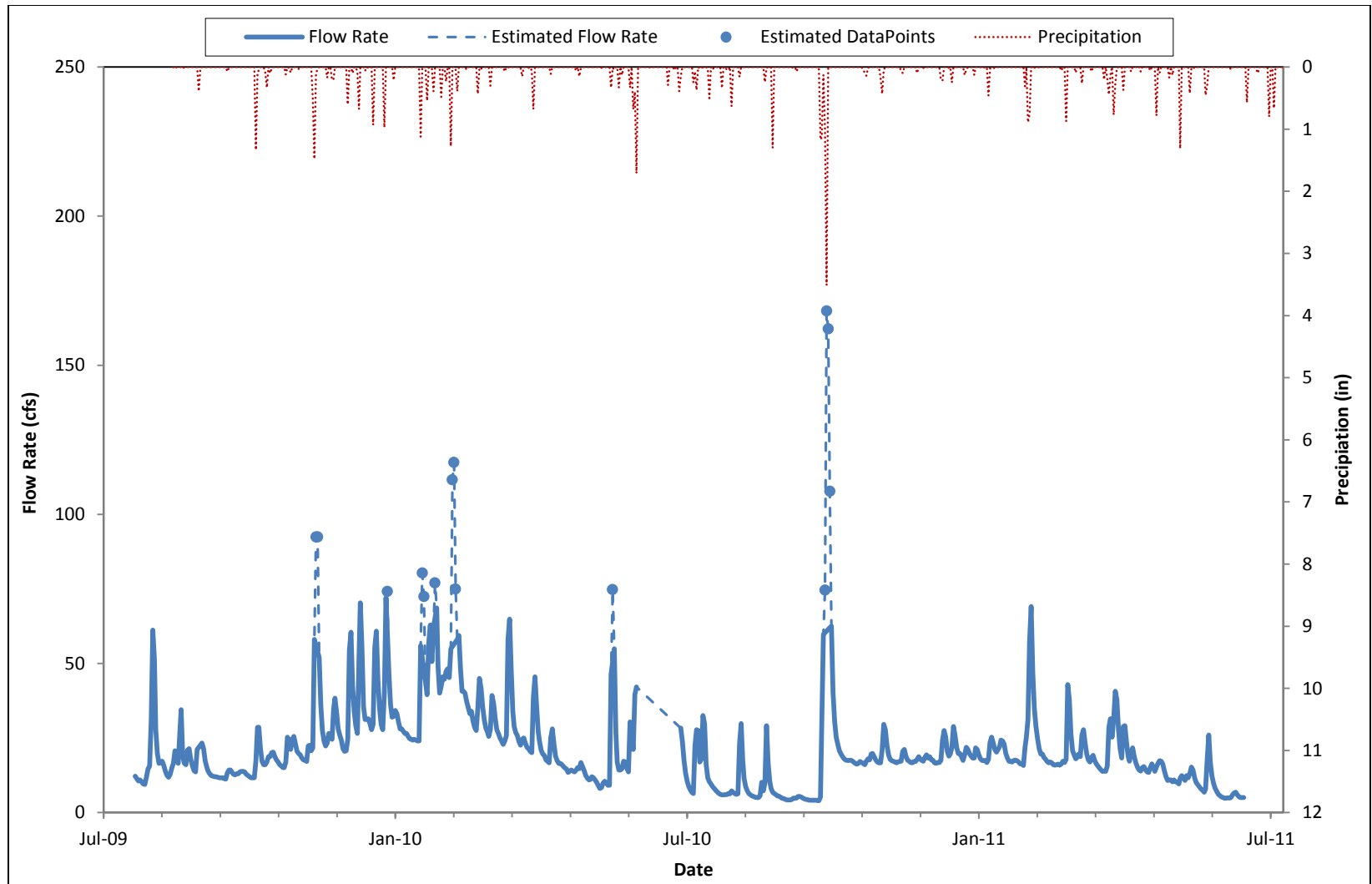


Figure C6-6: Crooked Creek (DNR) flow rate and precipitation record.

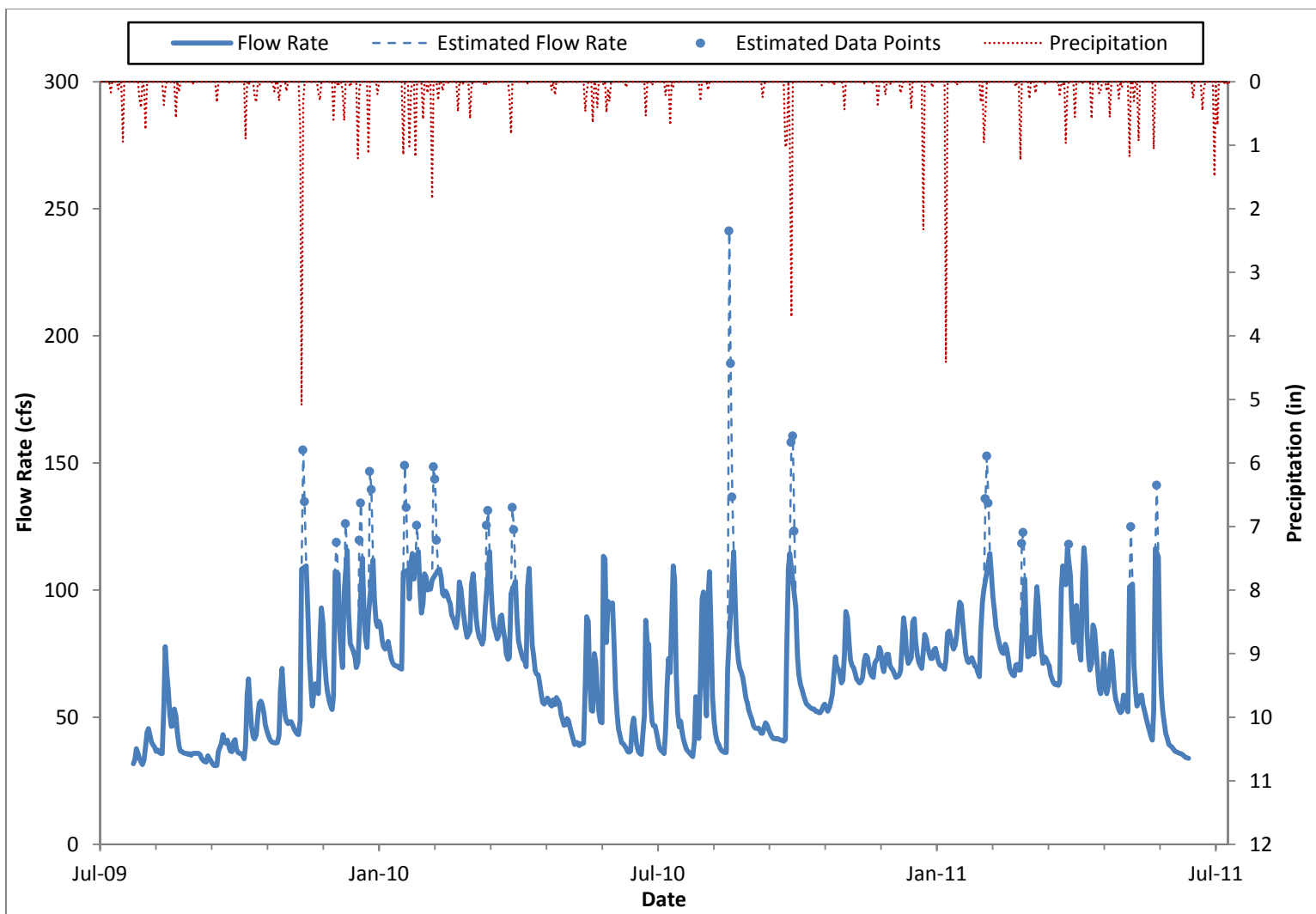


Figure C6-7: Juniper Creek (DNR) flow rate and precipitation record.

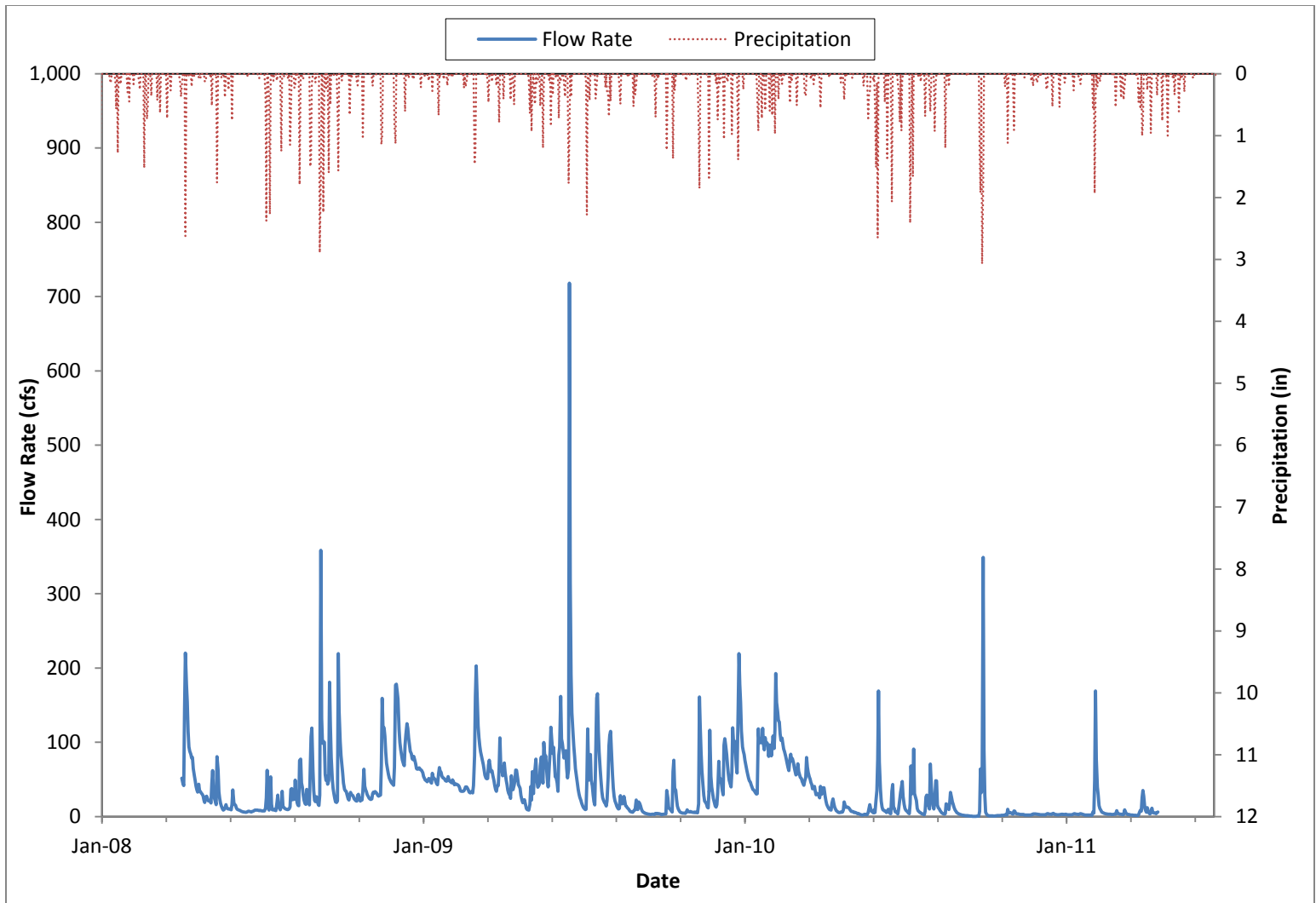


Figure C6-8: Jeffries Creek (USGS) flow rate and precipitation record.

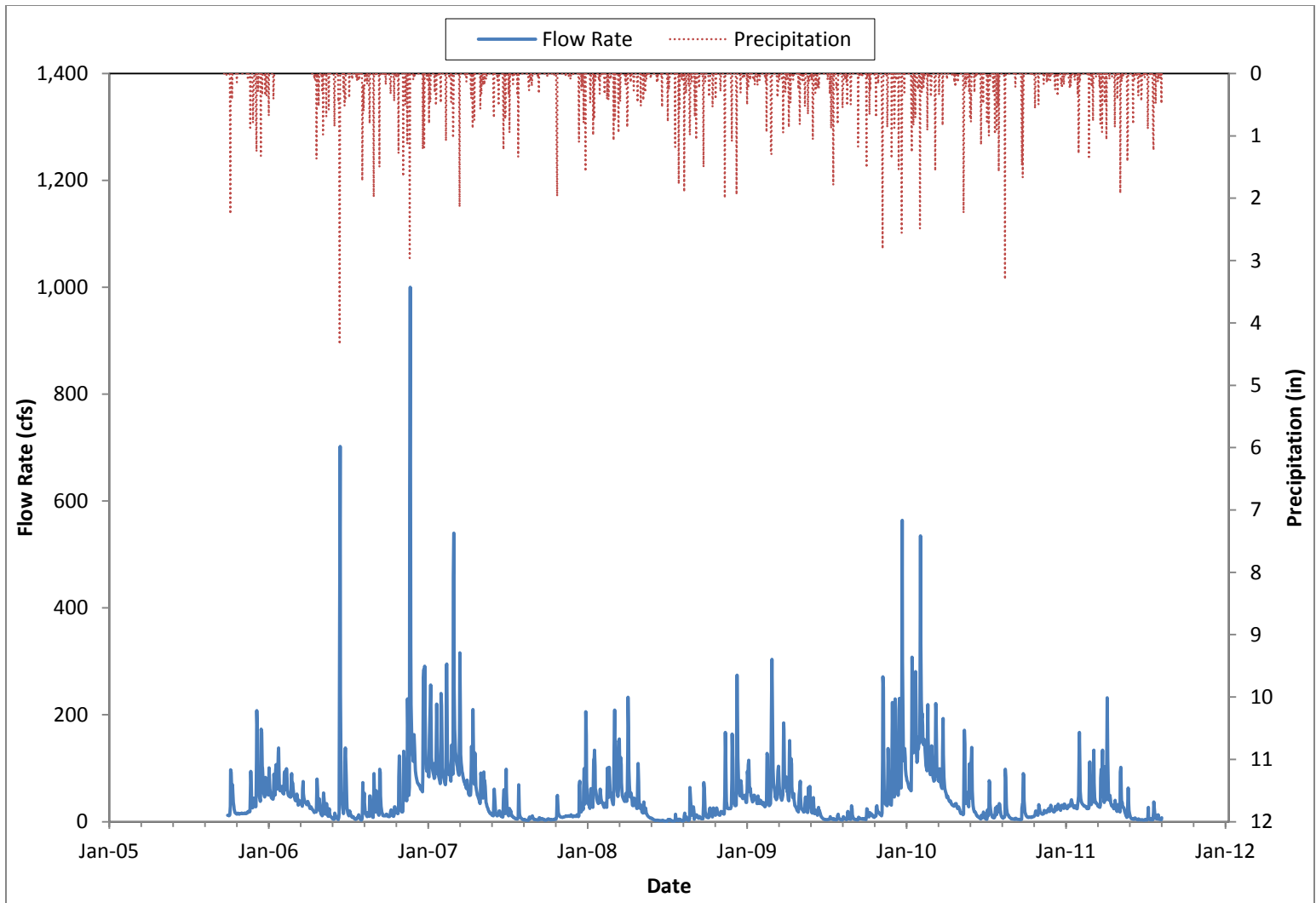


Figure C6-9: Black Creek below Chesterfield (USGS) flow rate and precipitation record.

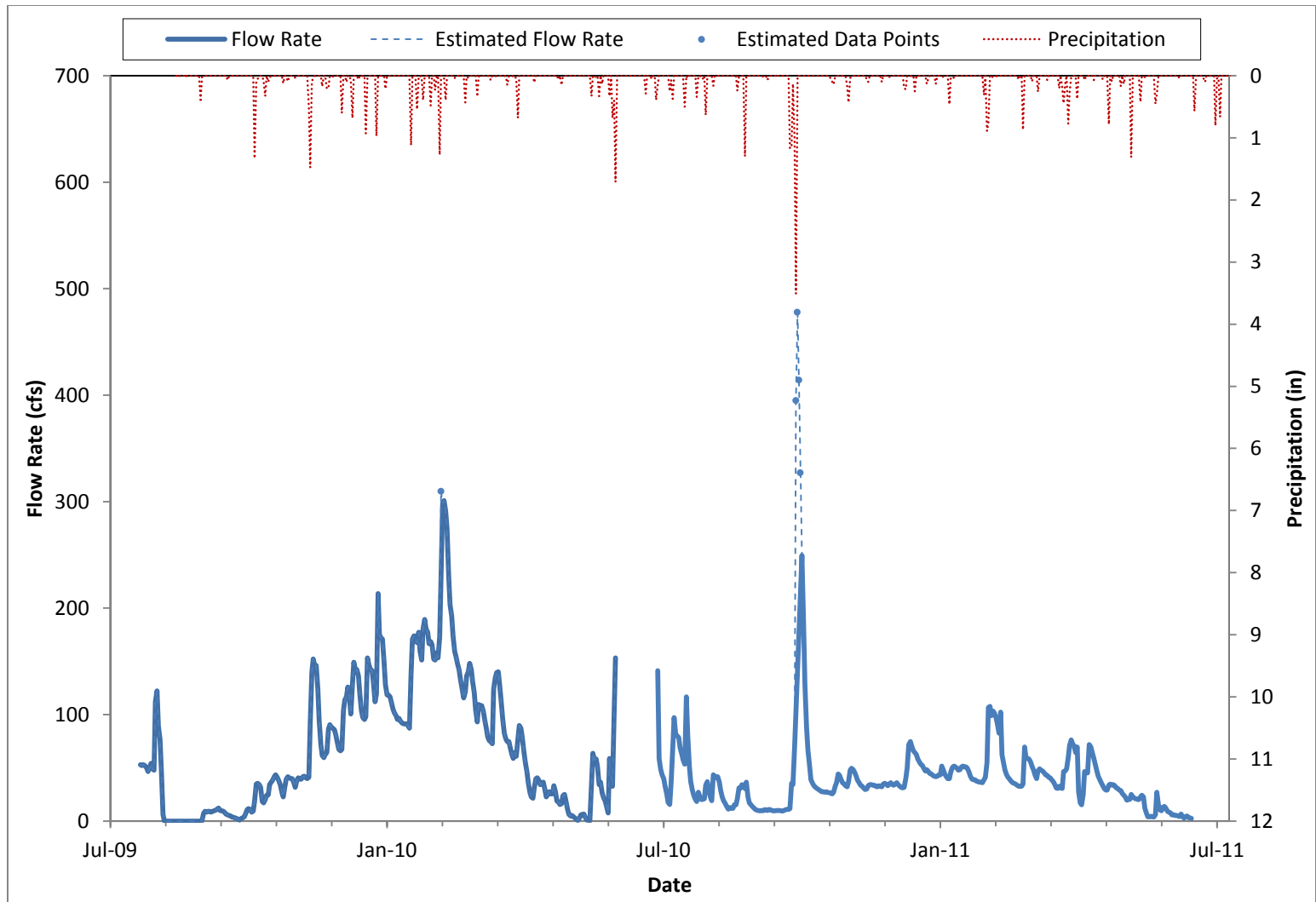


Figure C6-10: Crooked Creek flow rate and precipitation record.

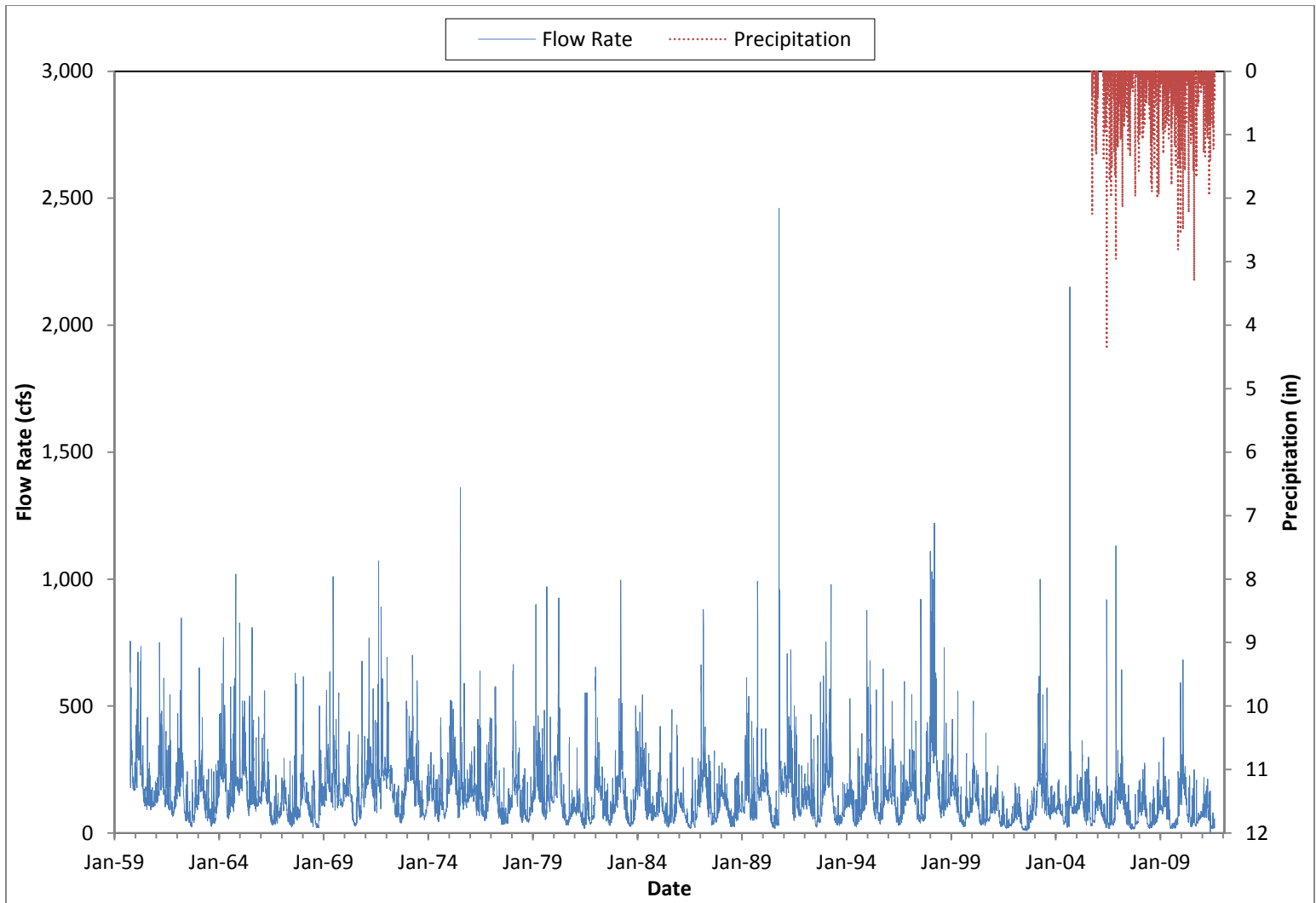


Figure C6-11: Black Creek near McBee (USGS) flow and available precipitation record

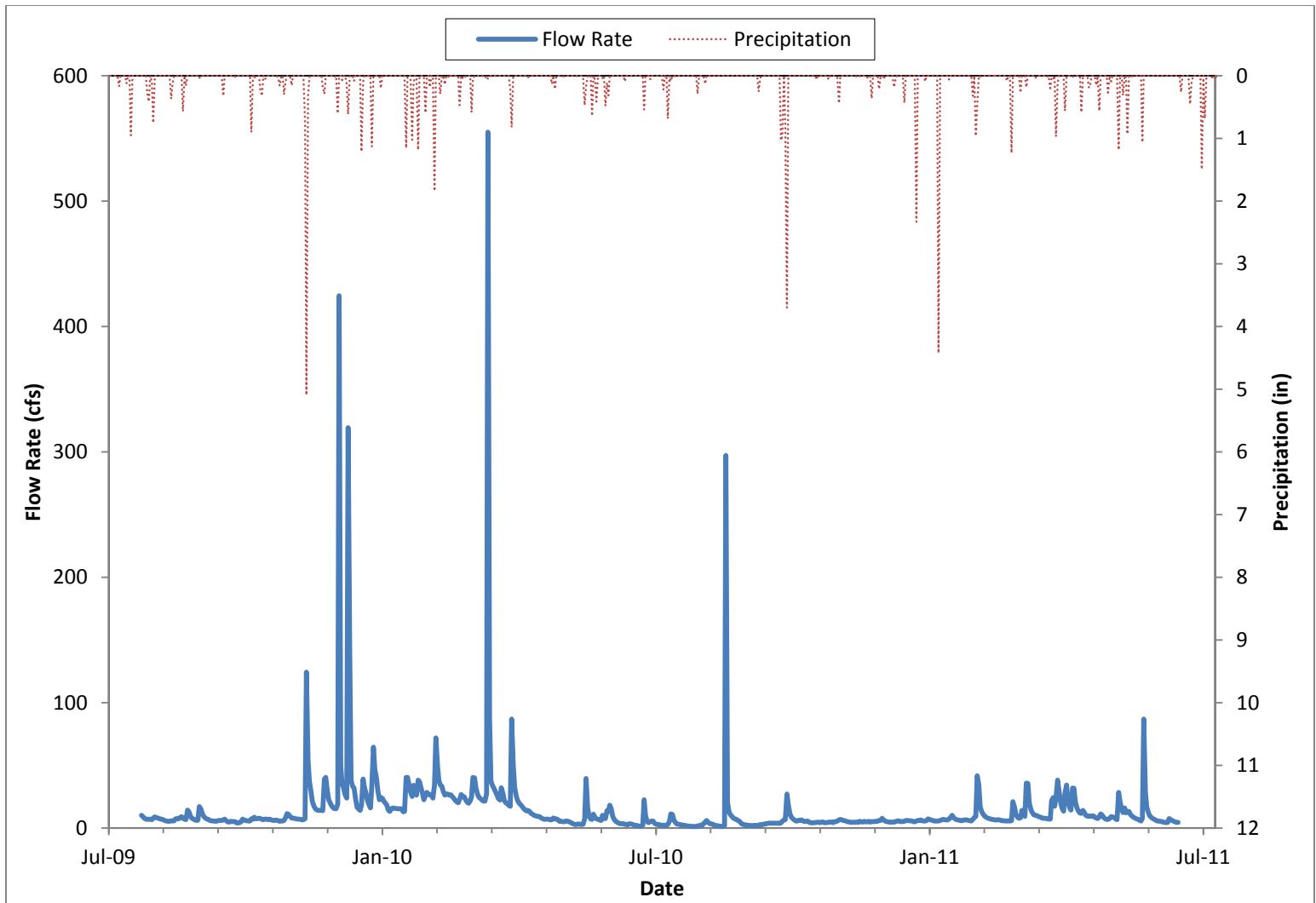


Figure C6-12: Thompson Creek flow rate and precipitation record.

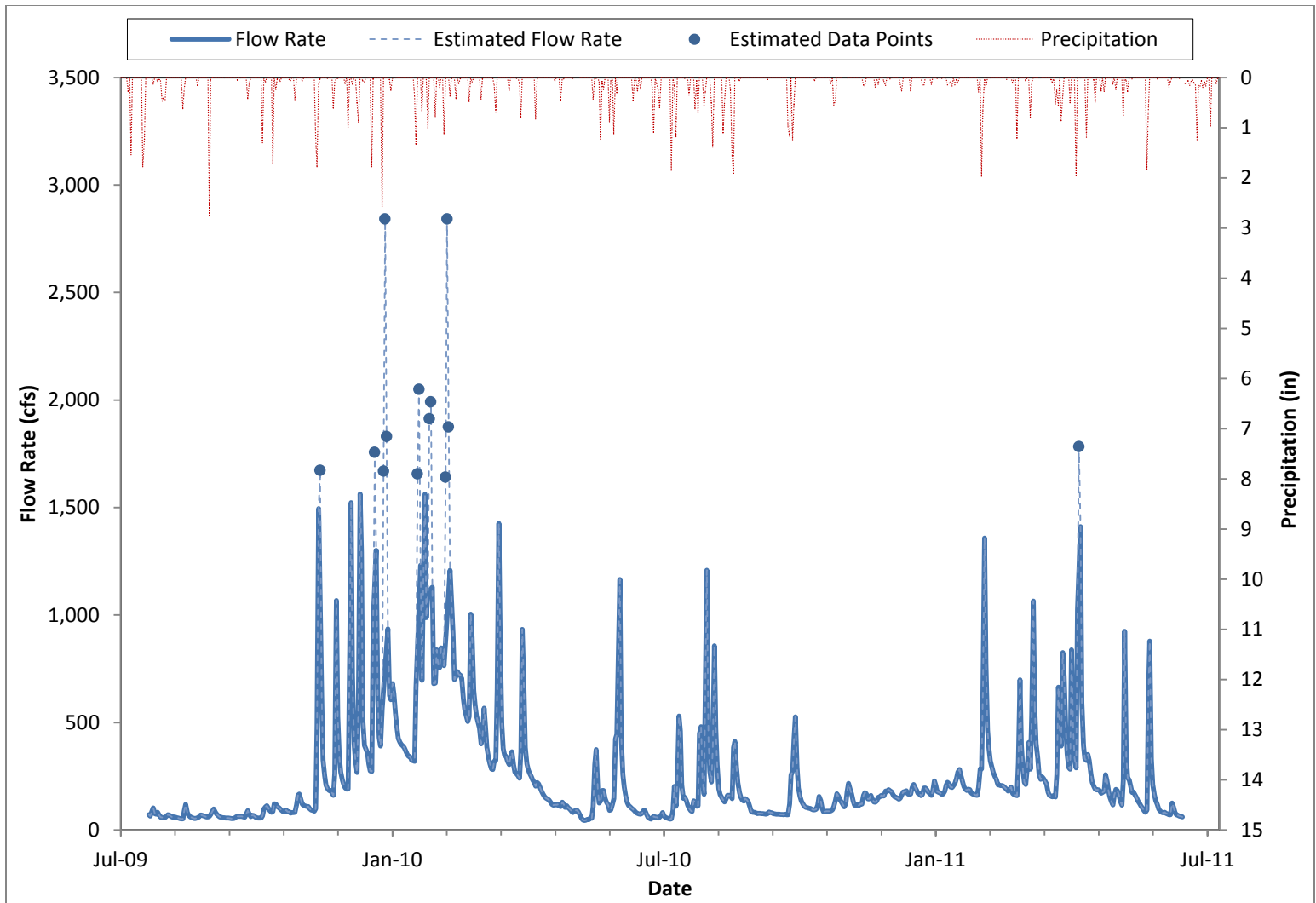


Figure C6-13: Lynch River flow rate and precipitation record.

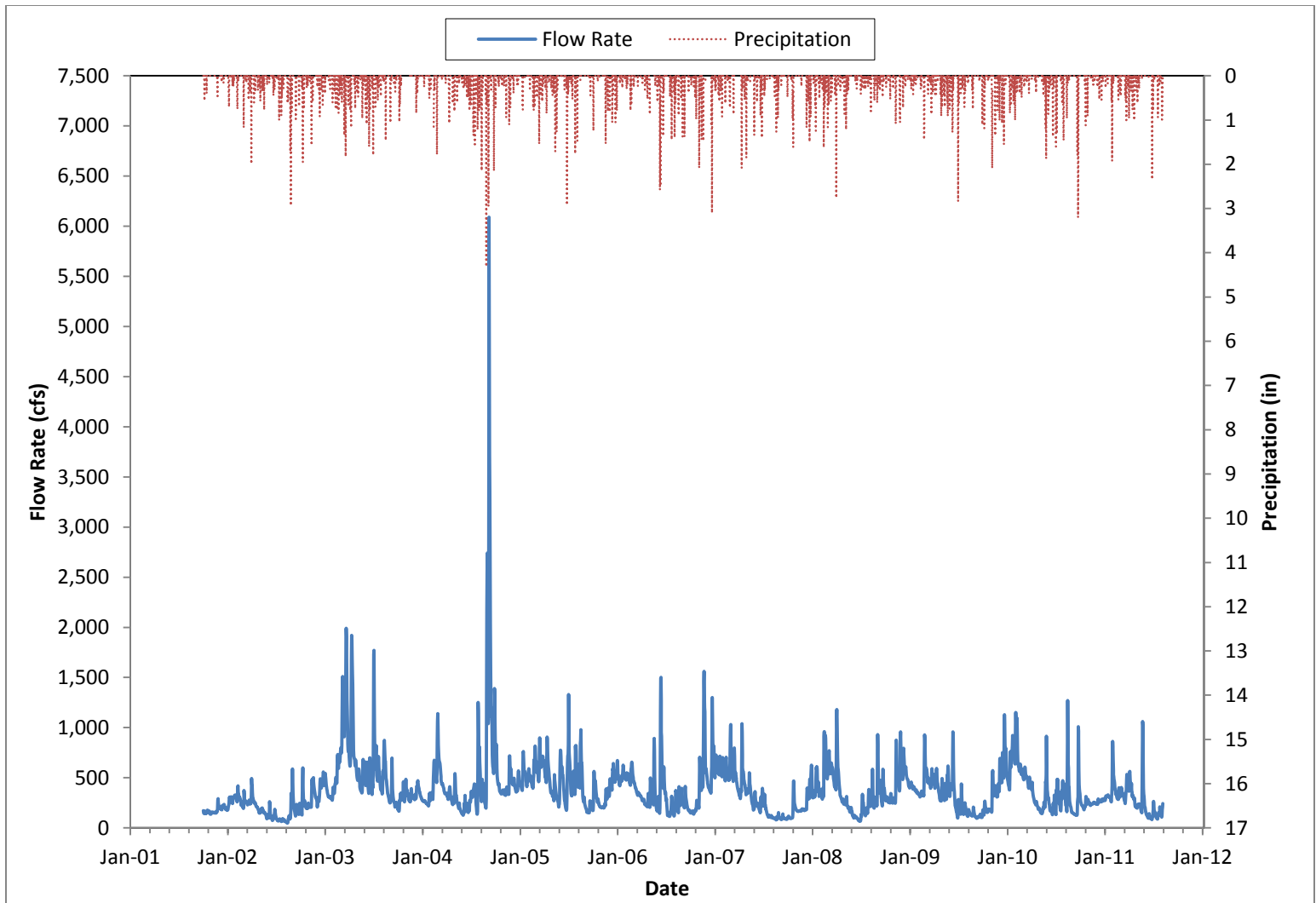


Figure C6-14: Black Creek near Quinby (USGS) flow and precipitation record

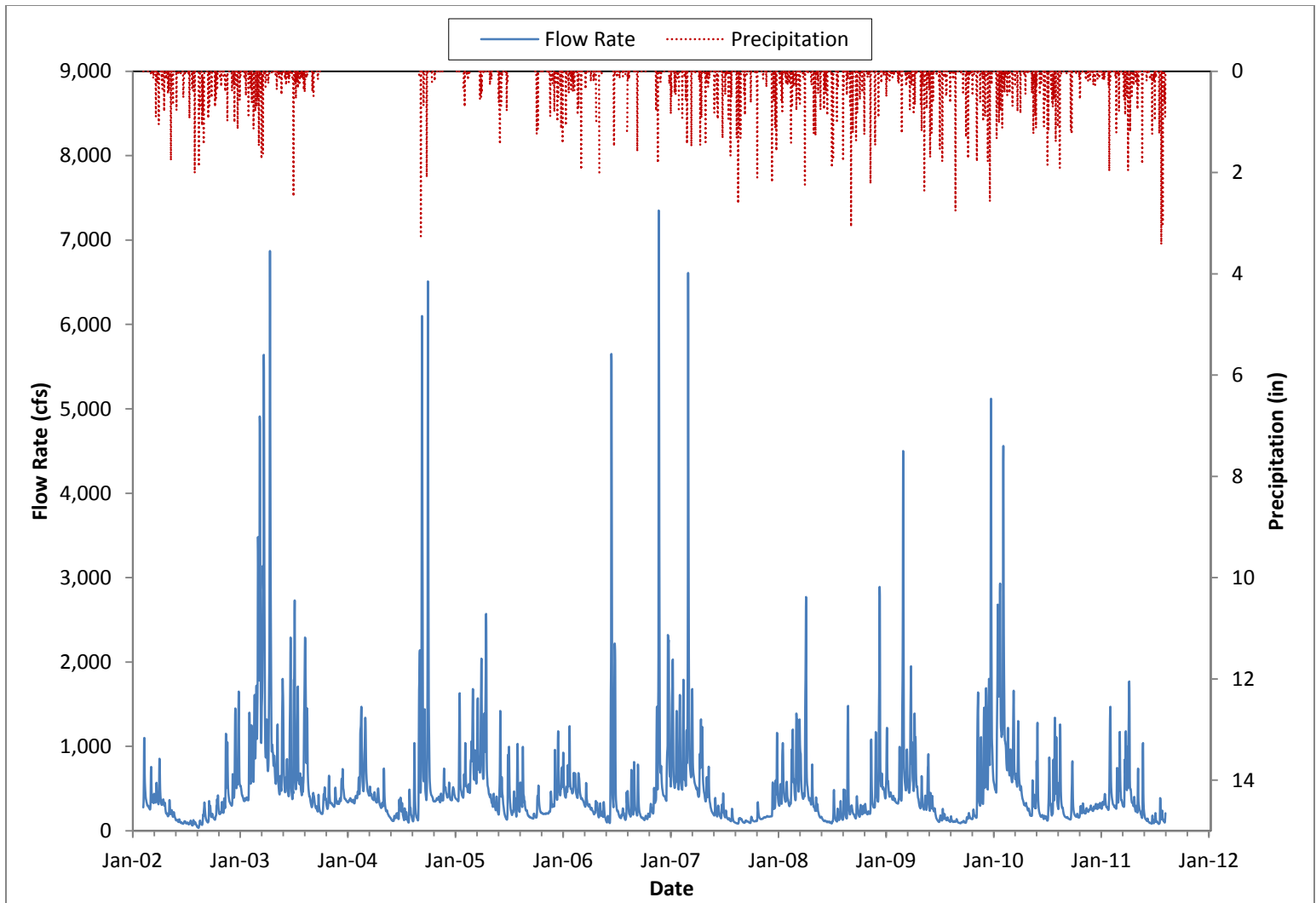


Figure C6-15: Lynch River near Bishopville (USGS) flow and precipitation record

APPENDIX C5: Stream Temperature Results

Seasonal and daily temperature trends

Note: The only data in this section is those where stage recorders were installed, and therefore all USGS sites are left out of this portion of the study. As a result, the numbering system in this appendix will differ from other appendices, but will still be ordered from smallest stream to largest.

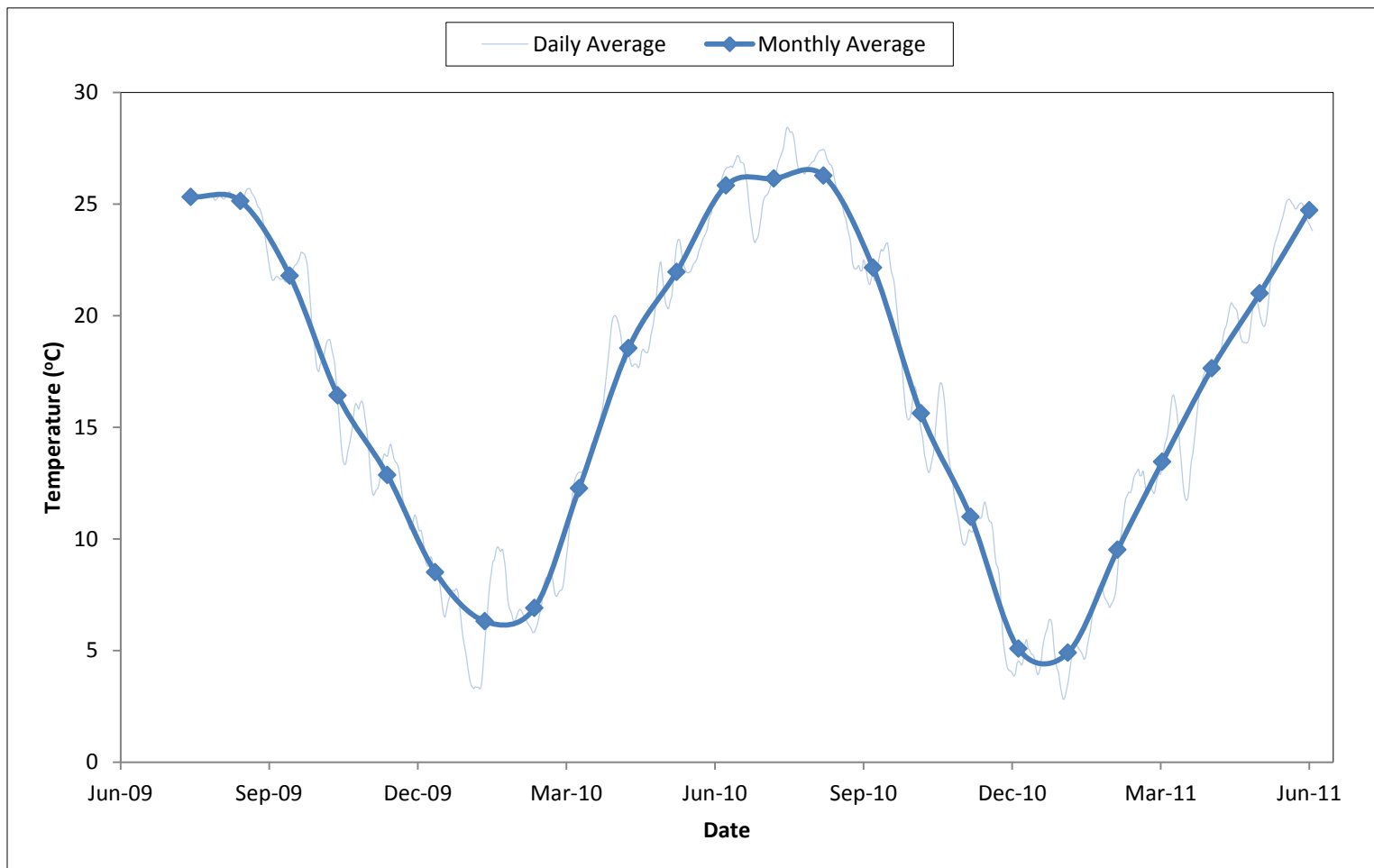


Figure C6-1: Monthly average and 7-day floating average temperatures of Huckleberry Branch.

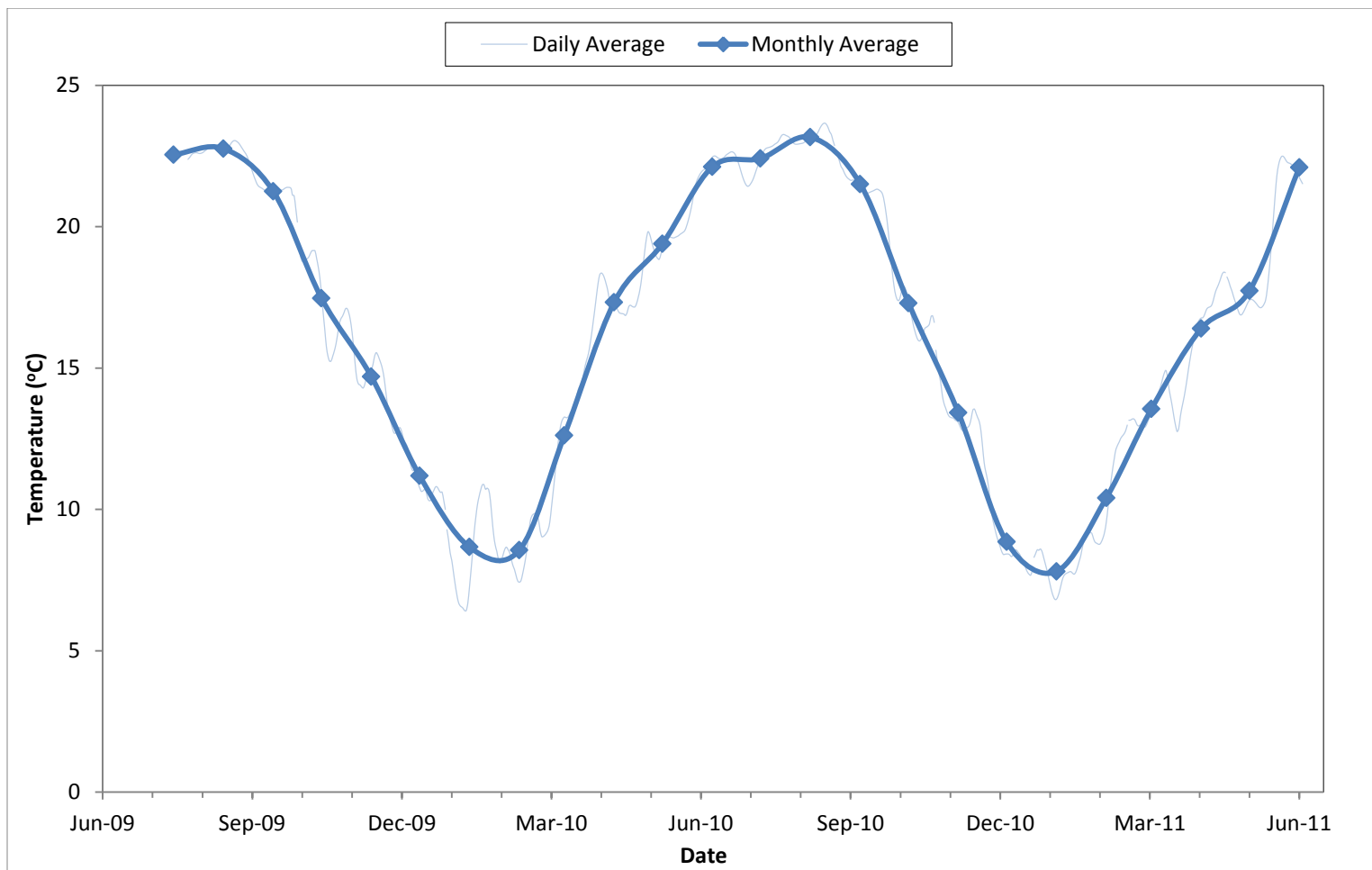


Figure C6-2: Monthly average and 7-day floating average temperatures of Jefferies Creek (DNR).

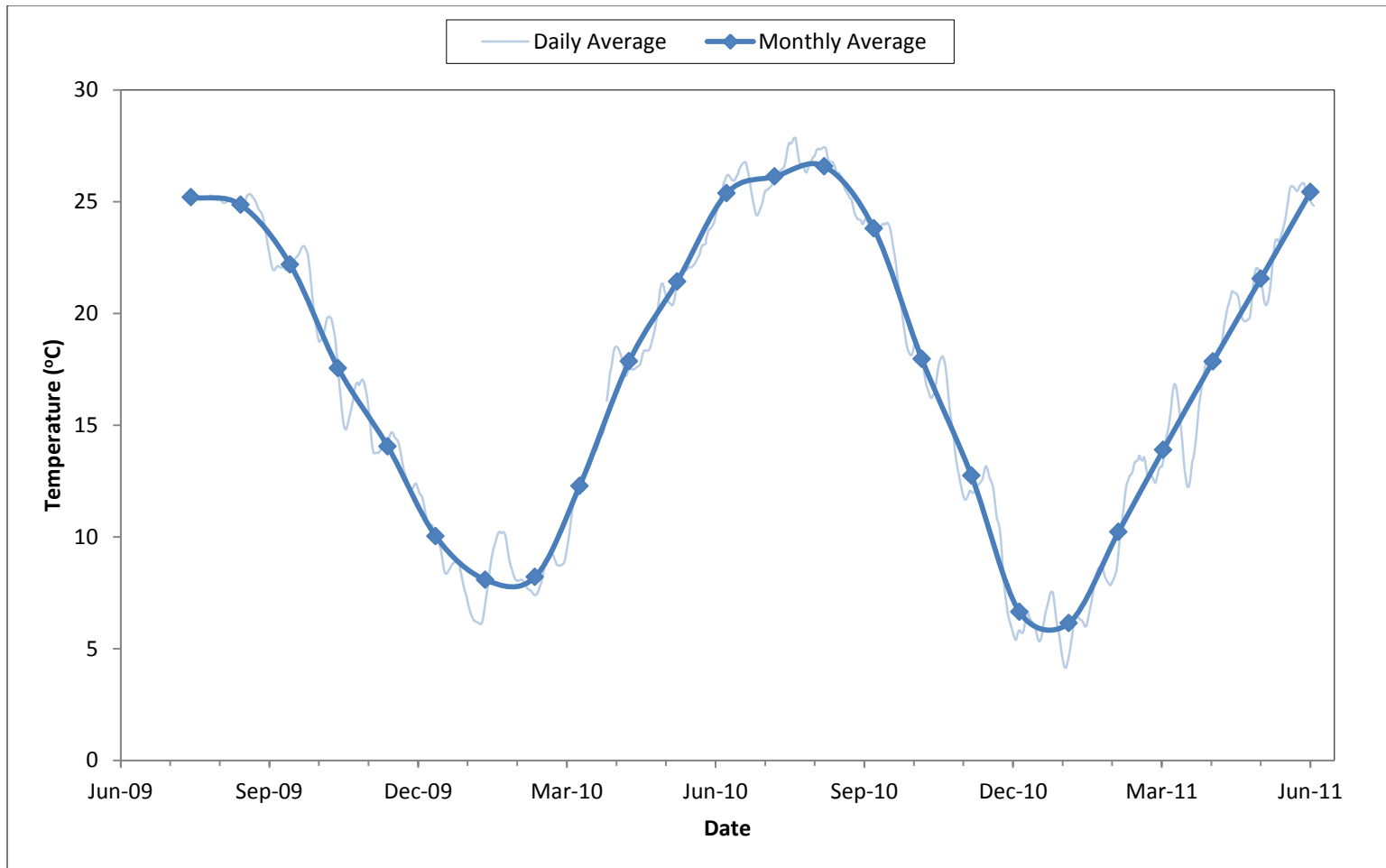


Figure C6-3: Monthly average and 7-day floating average temperatures of Hams Creek.

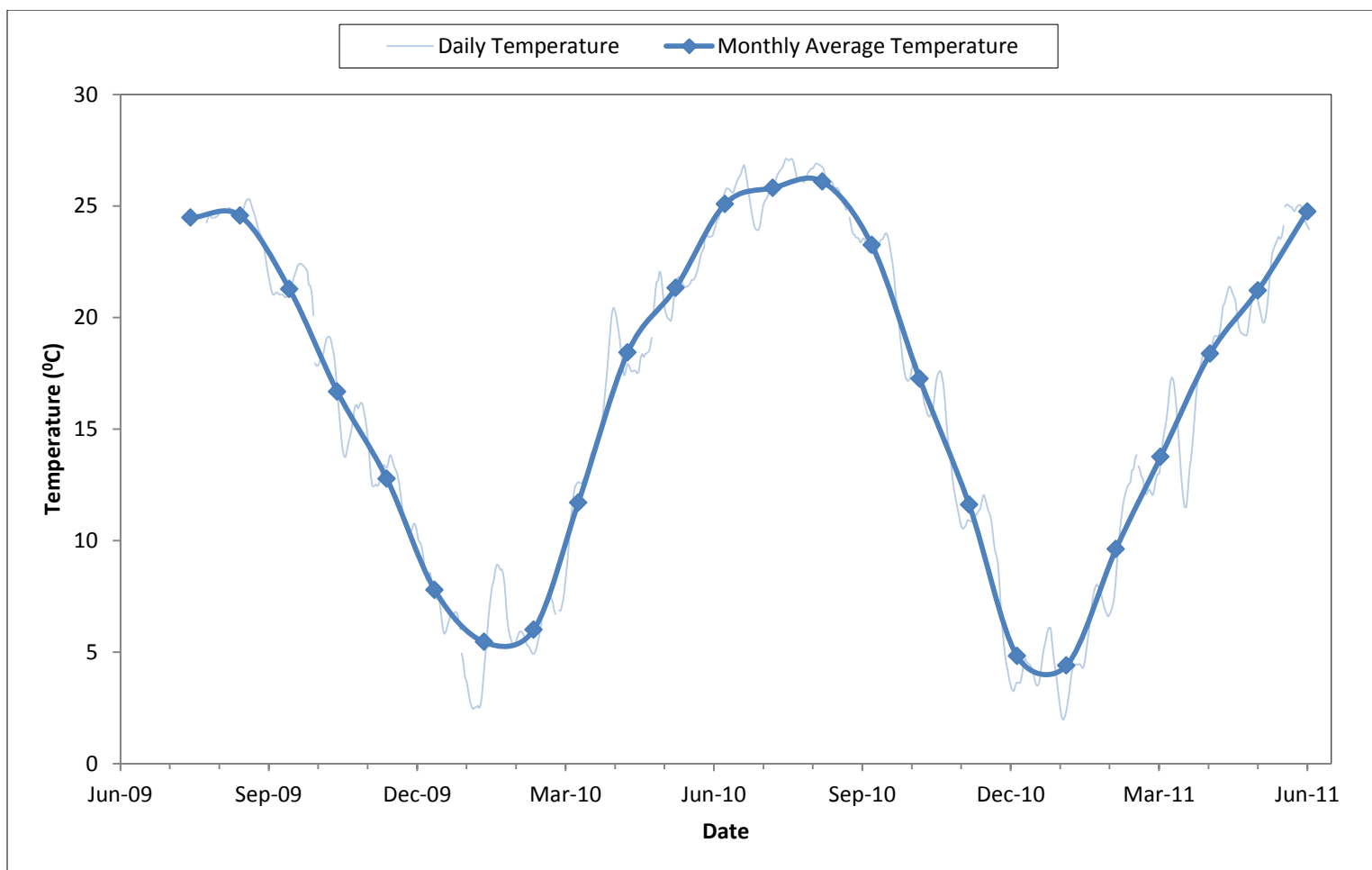


Figure C6-4: Monthly average and 7-day floating average temperatures of Juniper Creek.

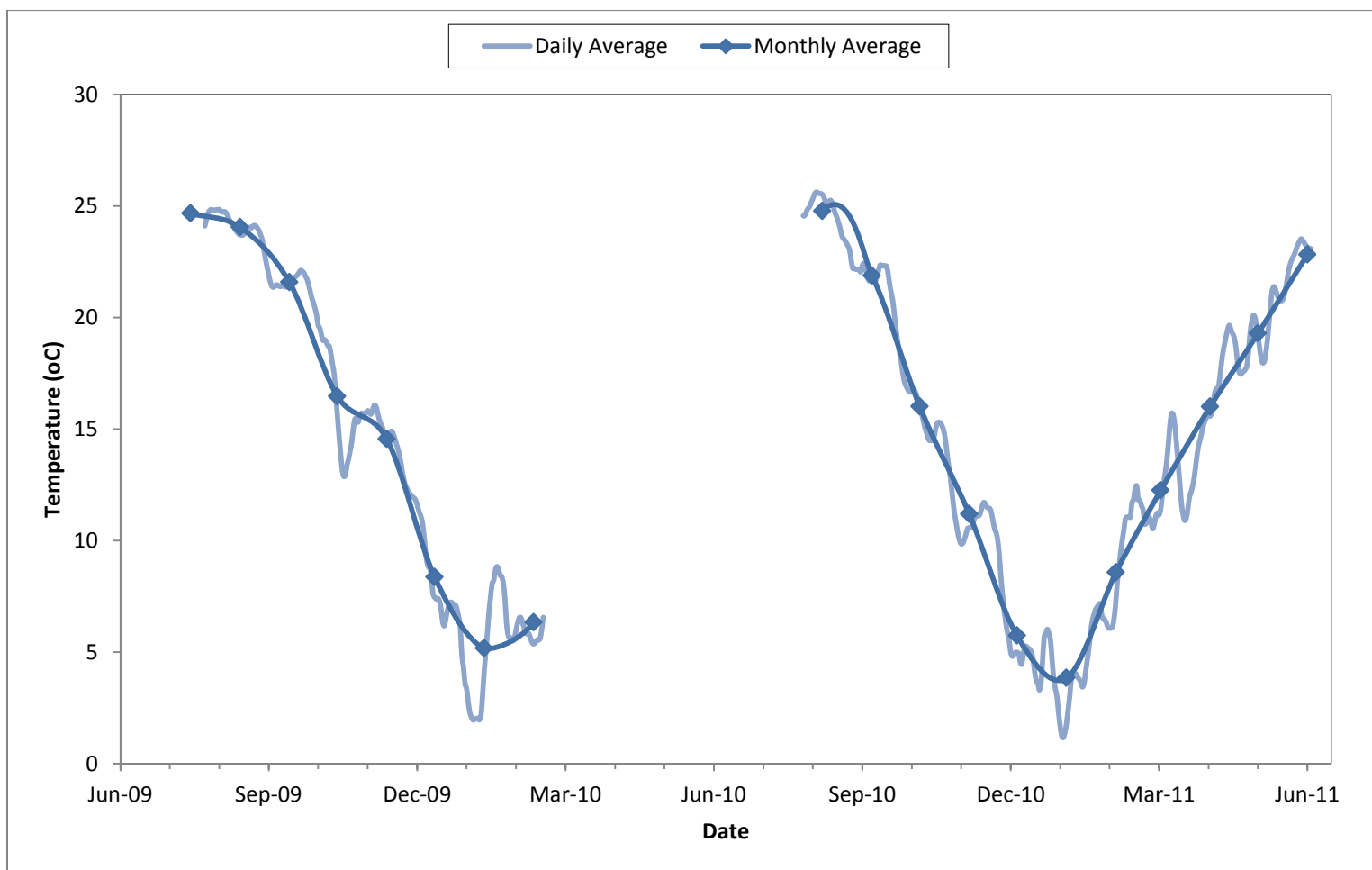


Figure C6-5: Monthly average and 7-day floating average temperatures of Little Lynches River

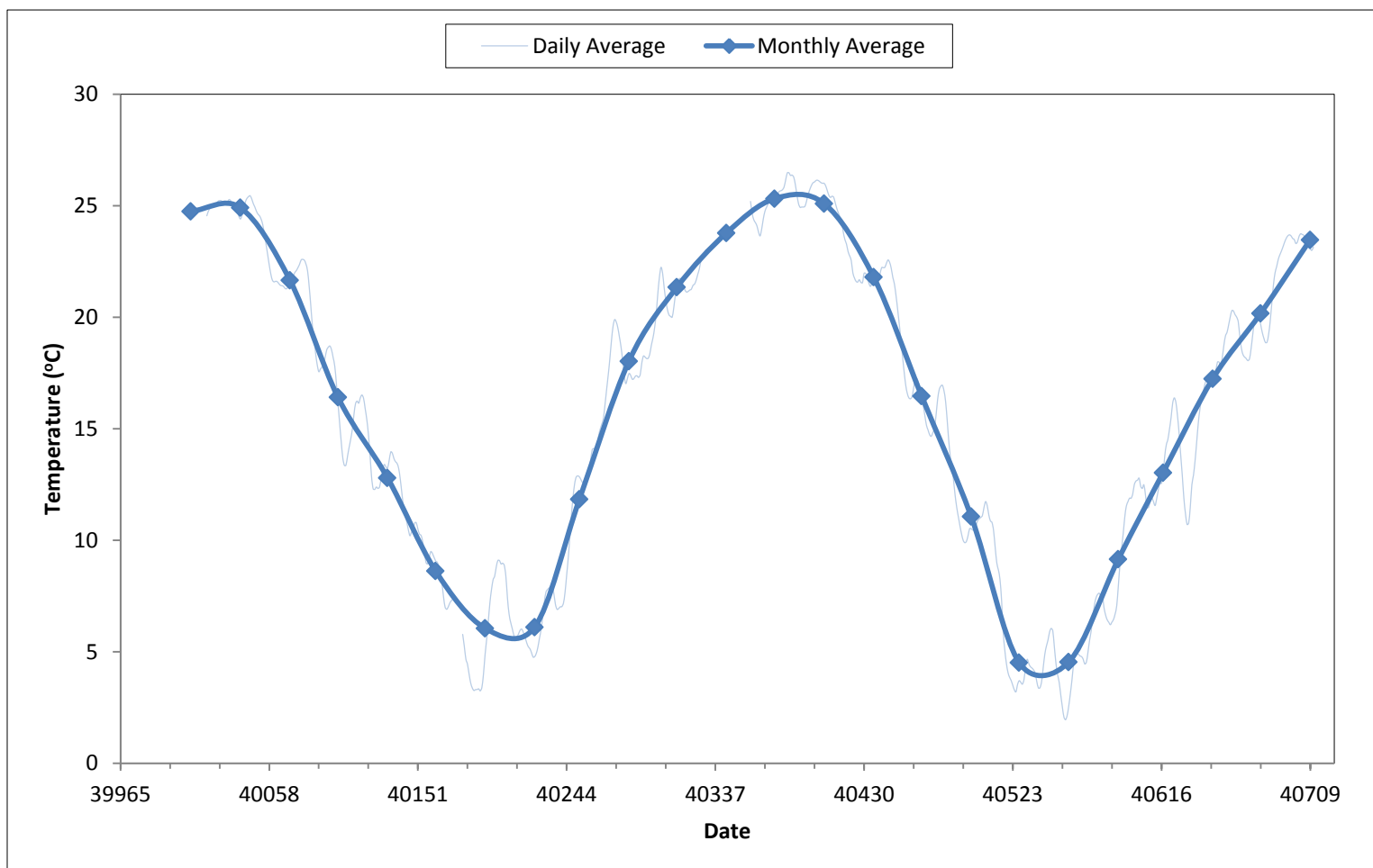


Figure C6-6: Monthly average and 7-day floating average temperatures of Crooked Creek (DNR).

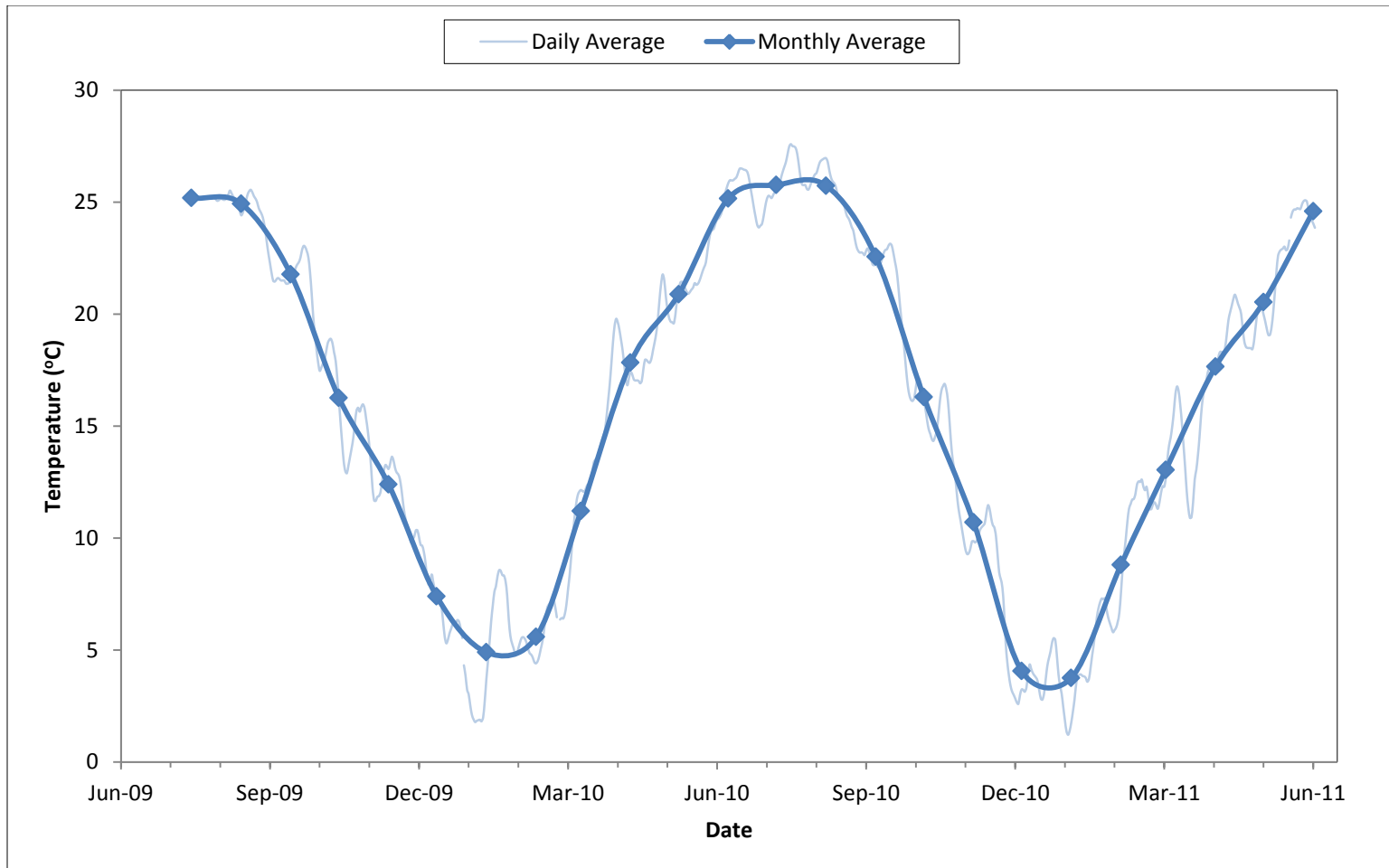


Figure C6-7: Monthly average and 7-day floating average temperatures of Juniper Creek (DNR).

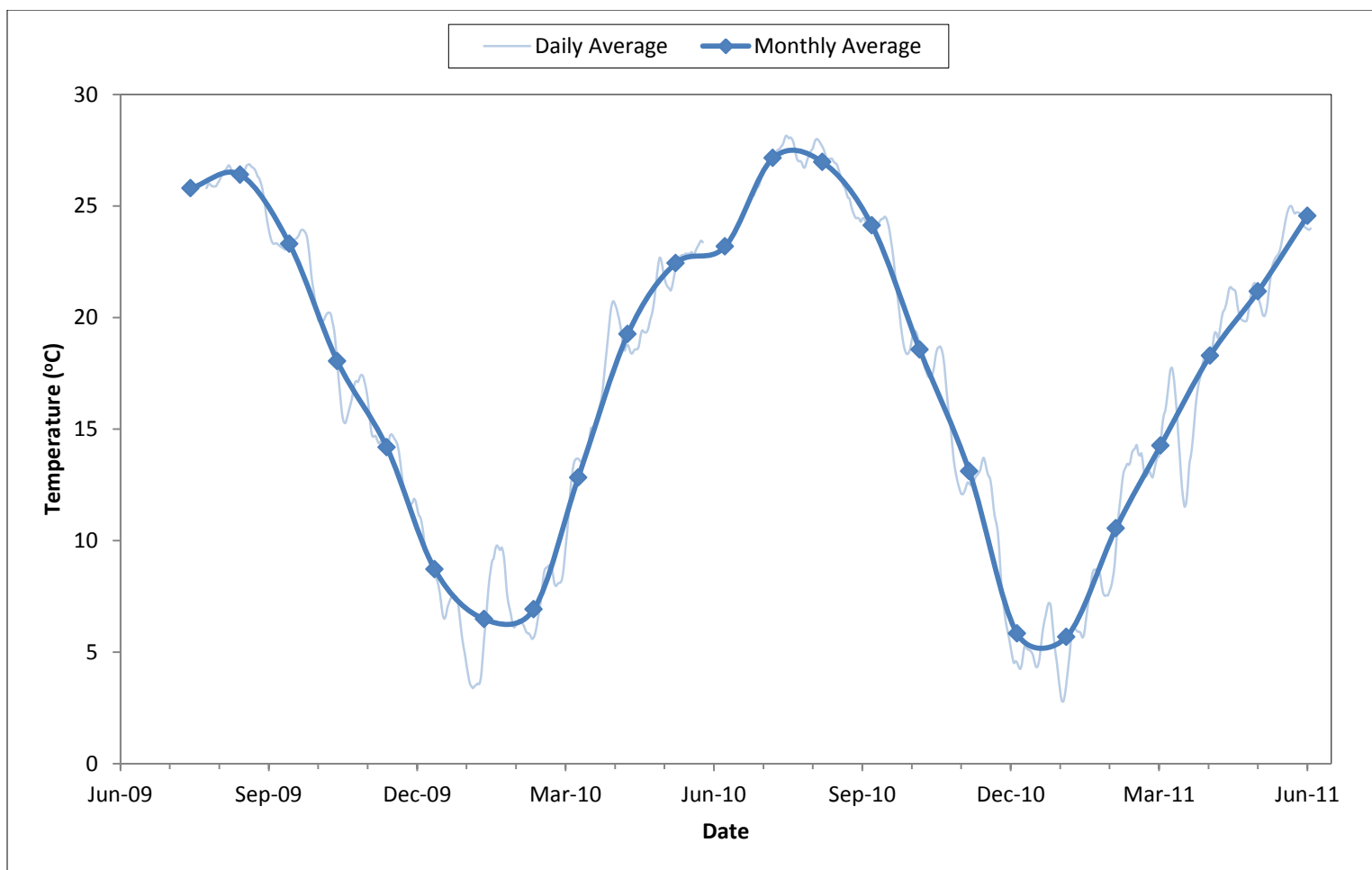


Figure C6-8: Monthly average and 7-day floating average temperatures of Crooked Creek.

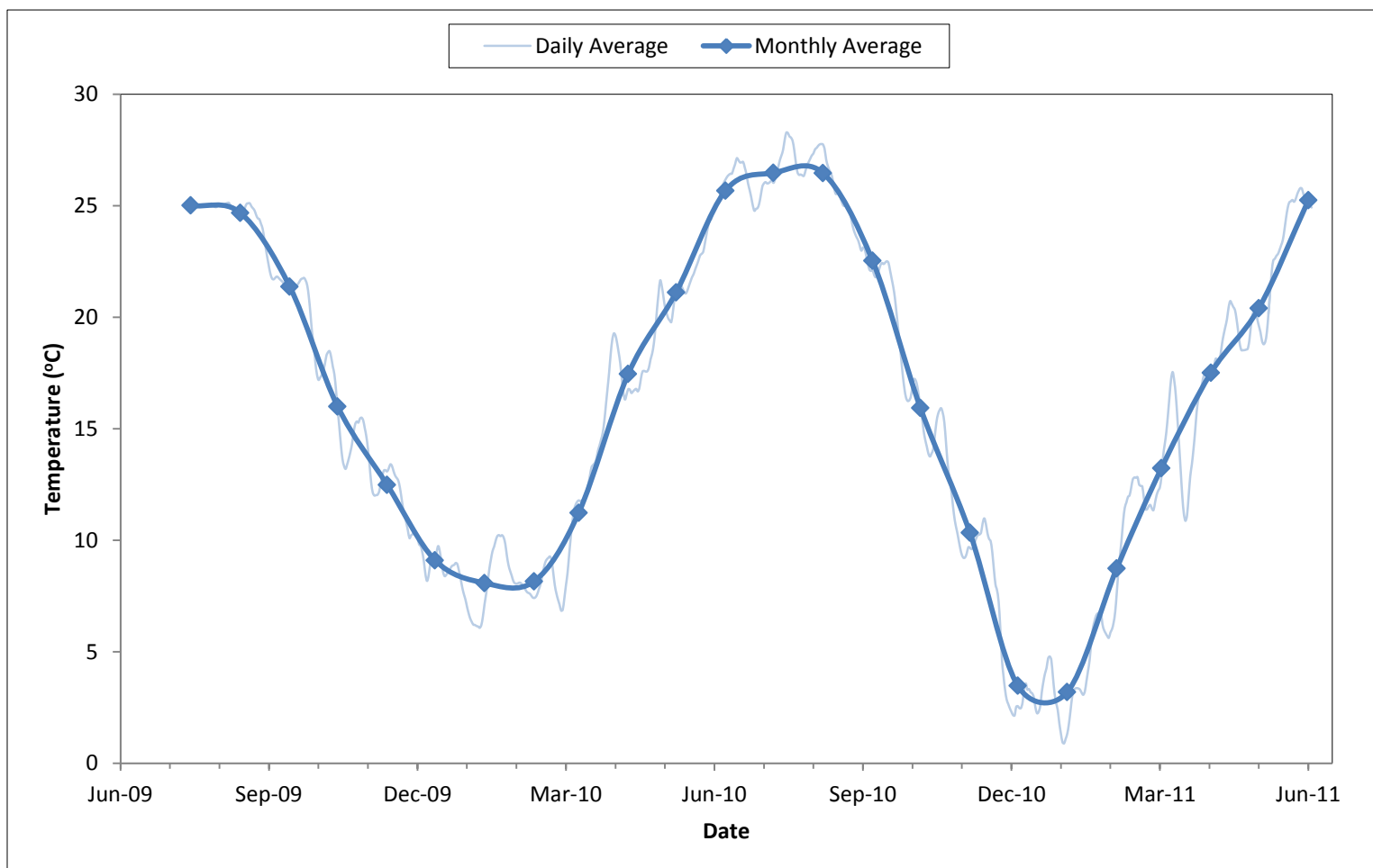


Figure C6-9: Monthly average and 7-day floating average temperatures of Thompson Creek.

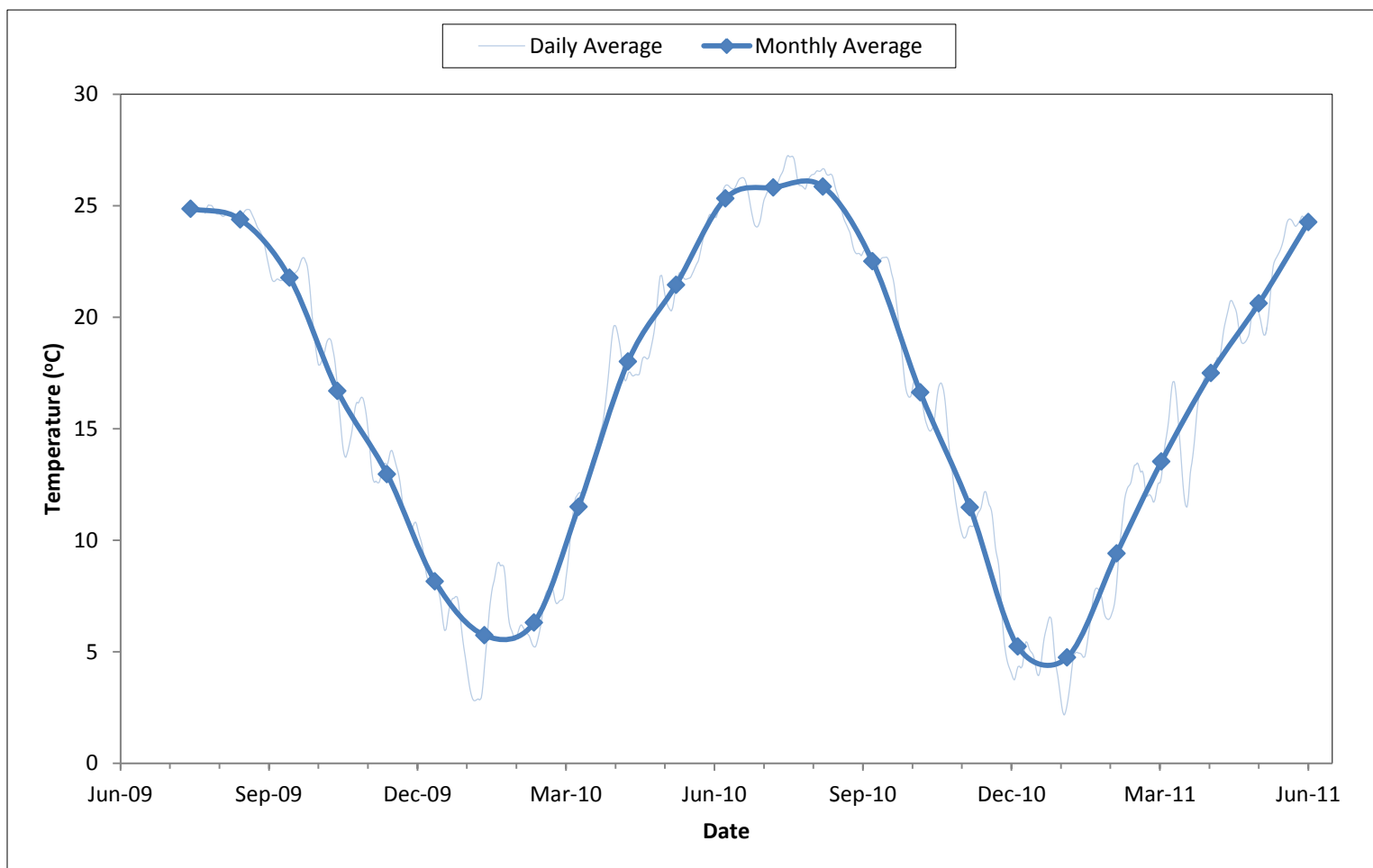


Figure C6-10: Monthly average and 7-day floating average temperatures of Lynches River.

APPENDIX C6: Daily Bed Load

Daily bed load in (tons/day).

Note: These are strictly estimated bed loads that are based upon Brownlie's equations.

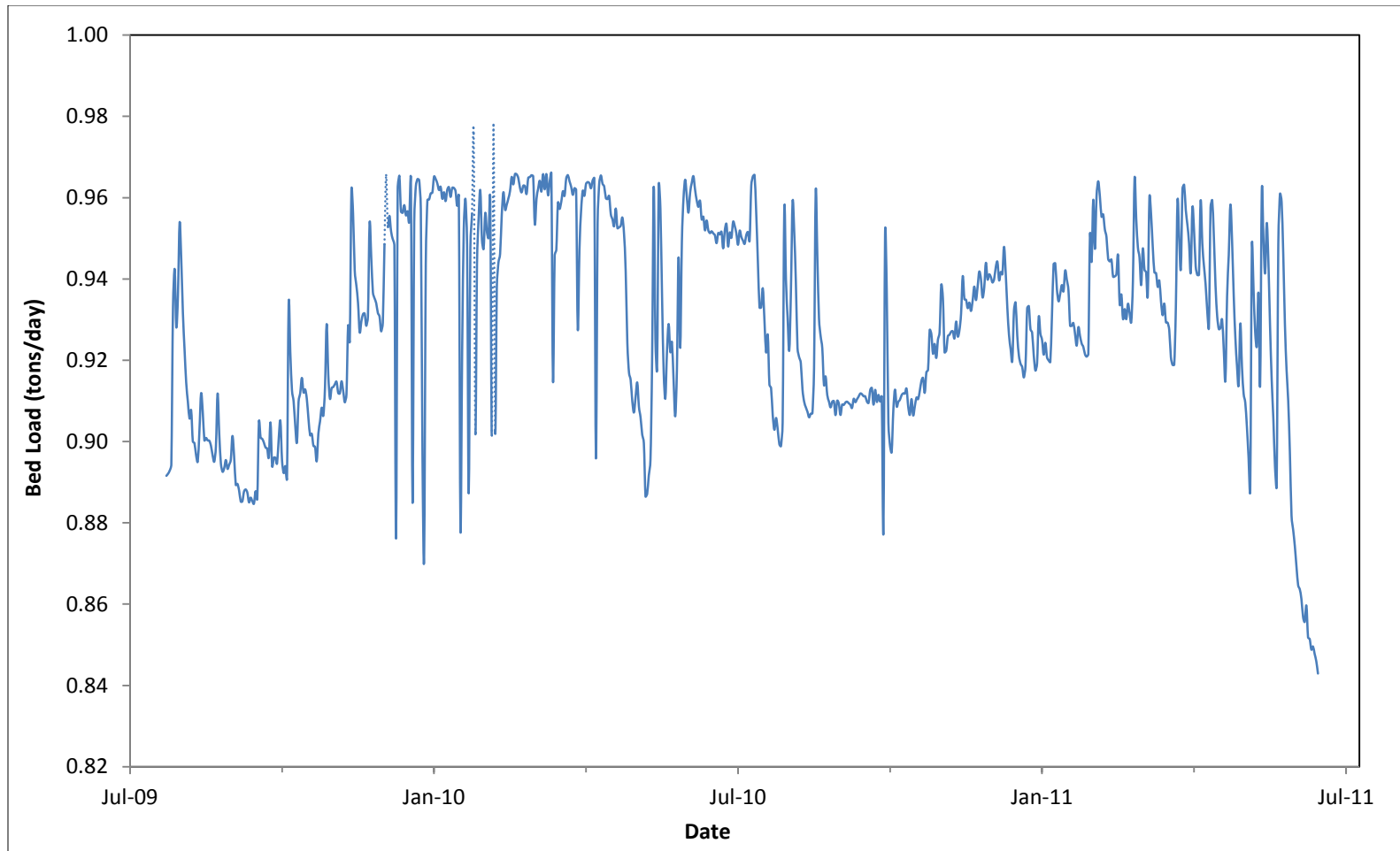


Figure C6-1: Sediment flux (tons/day) based upon daily flow averages of Huckleberry Branch. The solid lines are calculated from flow rates within the cross section surveyed while the dotted lines are based upon projected flow rates that exceed the boundaries of the channel survey.

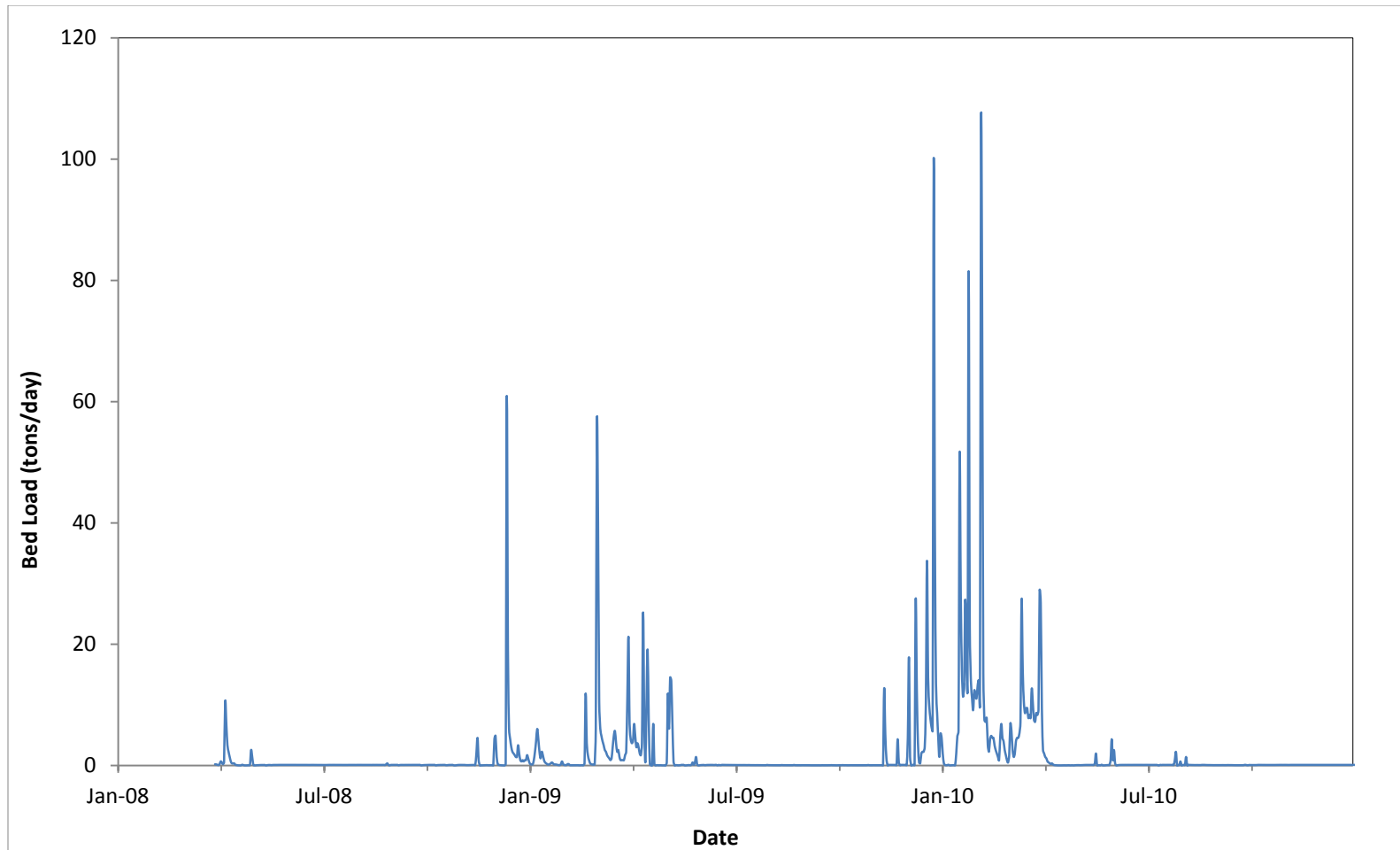


Figure C6-2: Sediment flux (tons/day) based upon daily flow averages of Little Fork Creek (USGS). The solid lines are calculated from flow rates within the cross section surveyed while the dotted lines are based upon projected flow rates that exceed the boundaries of the channel survey.

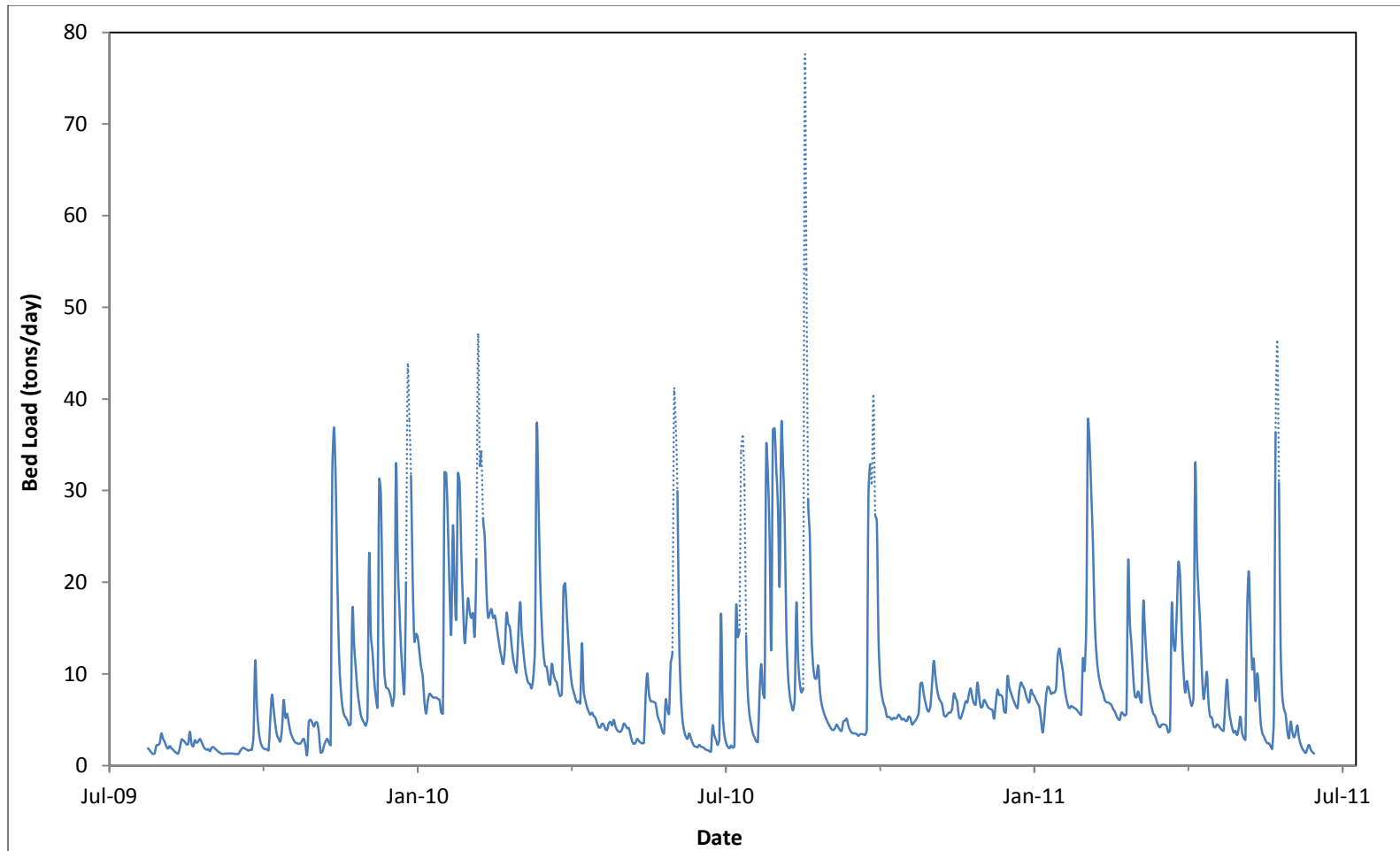


Figure C6-3: Sediment flux (tons/day) based upon daily flow averages of Hams Creek. The solid lines are calculated from flow rates within the cross section surveyed while the dotted lines are based upon projected flow rates that exceed the boundaries of the channel survey.

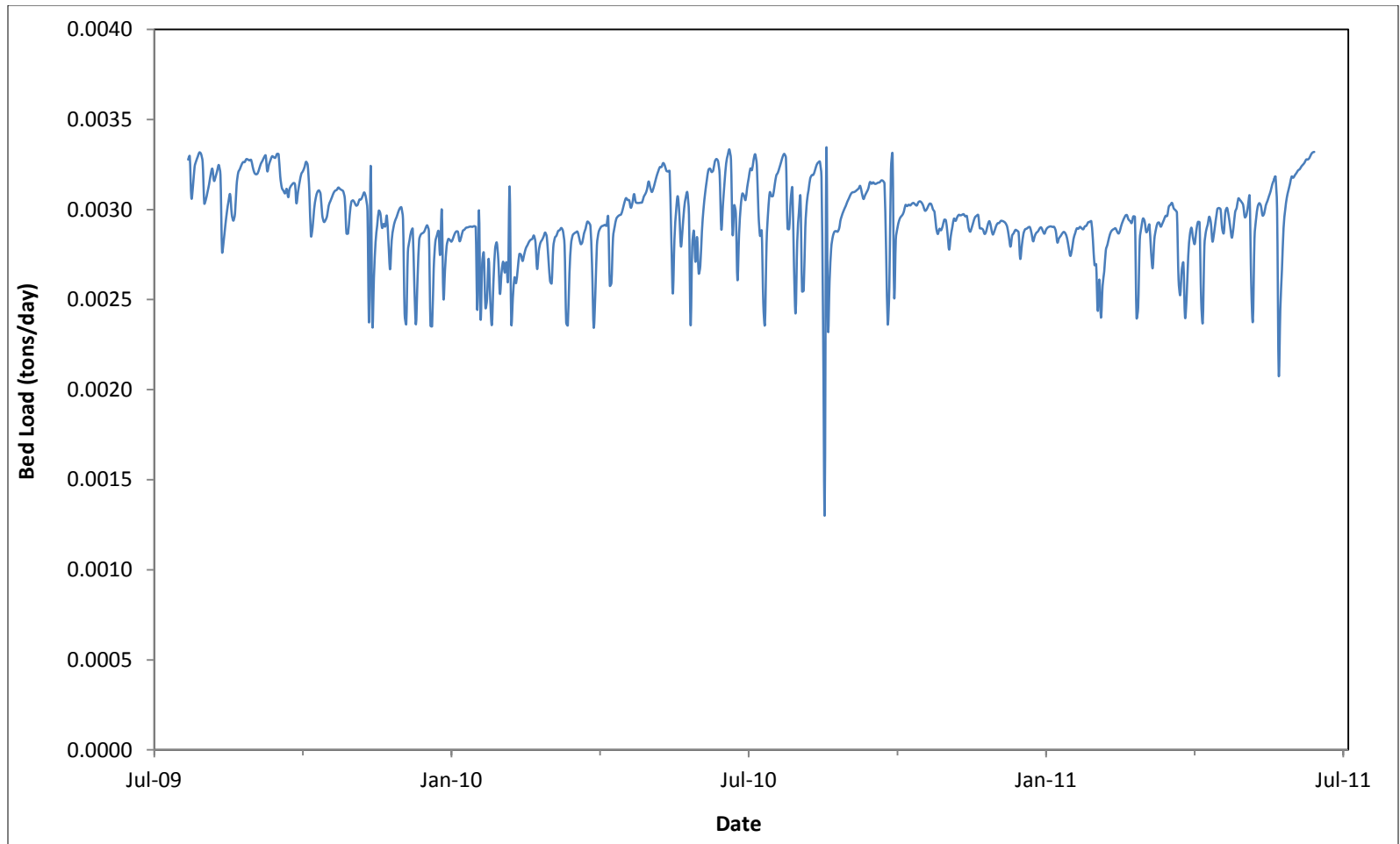


Figure C6-4: Sediment flux (tons/day) based upon daily flow averages of Juniper Creek. The solid lines are calculated from flow rates within the cross section surveyed while the dotted lines are based upon projected flow rates that exceed the boundaries of the channel survey.

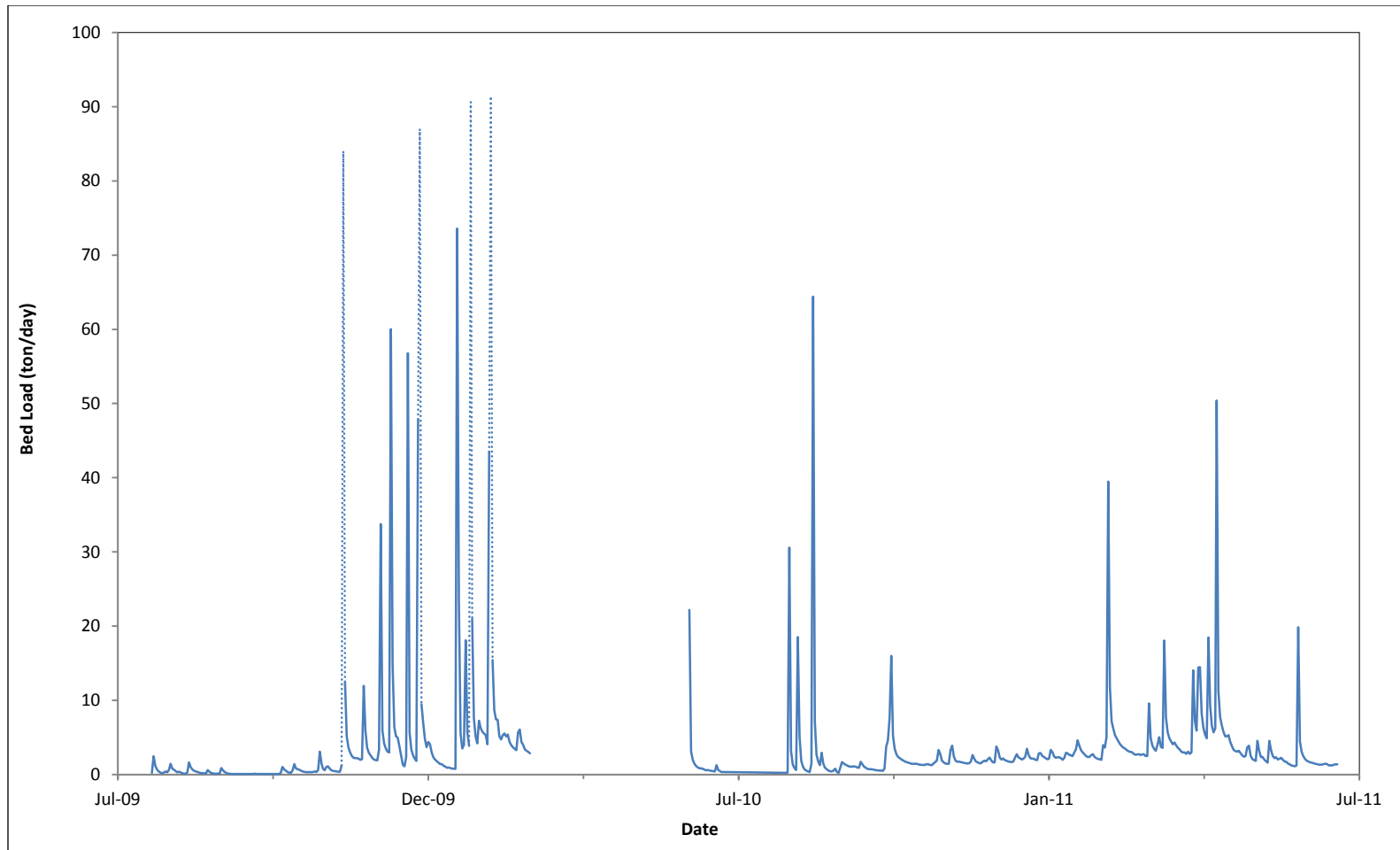


Figure C6-5: Sediment flux (tons/day) based upon daily flow averages of Little Lynchies River. The solid lines are calculated from flow rates within the cross section surveyed while the dotted lines are based upon projected flow rates that exceed the boundaries of the channel survey.

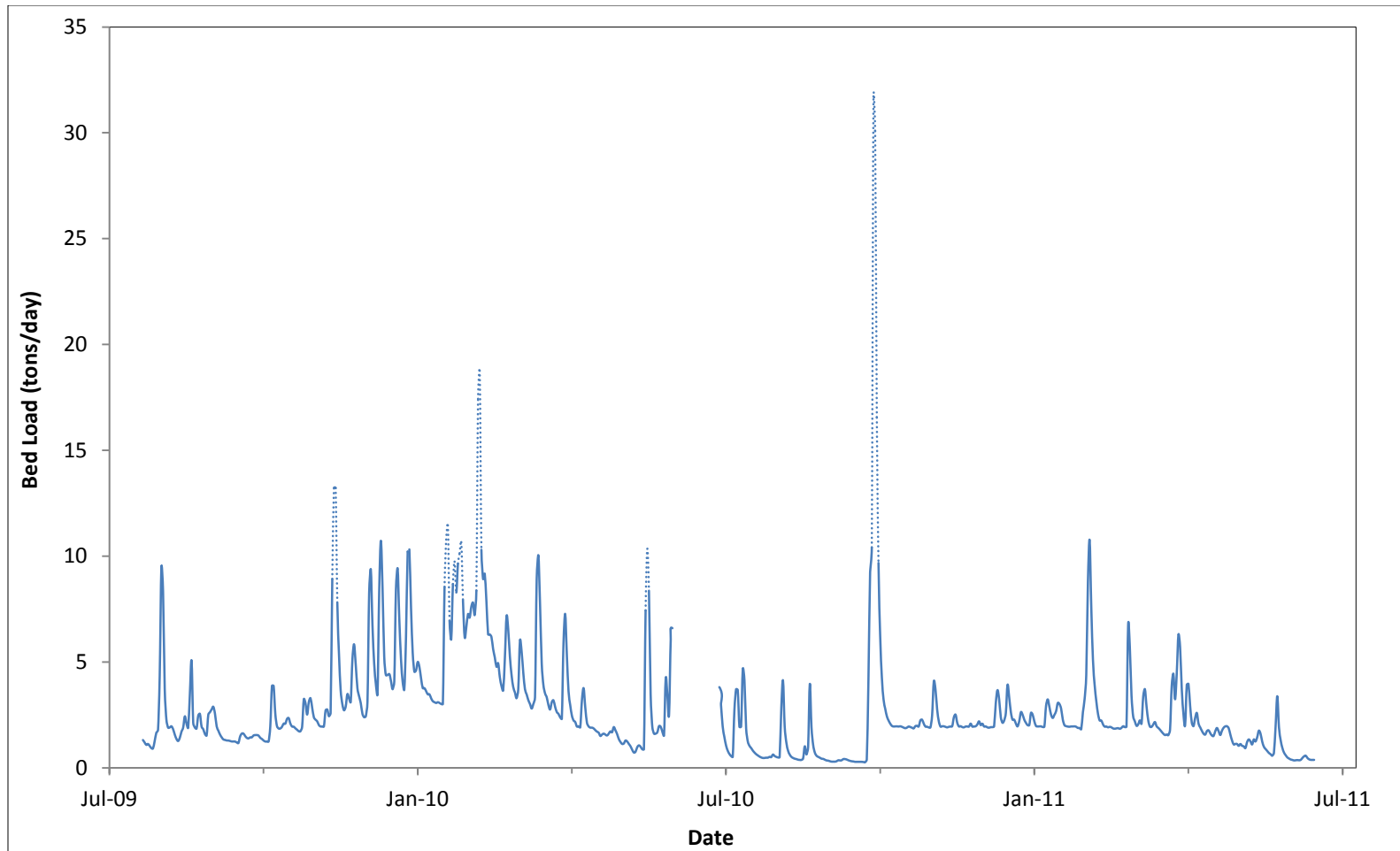


Figure C6-6: Sediment flux (tons/day) based upon daily flow averages of Crooked Creek (DNR). The solid lines are calculated from flow rates within the cross section surveyed while the dotted lines are based upon projected flow rates that exceed the boundaries of the channel survey.

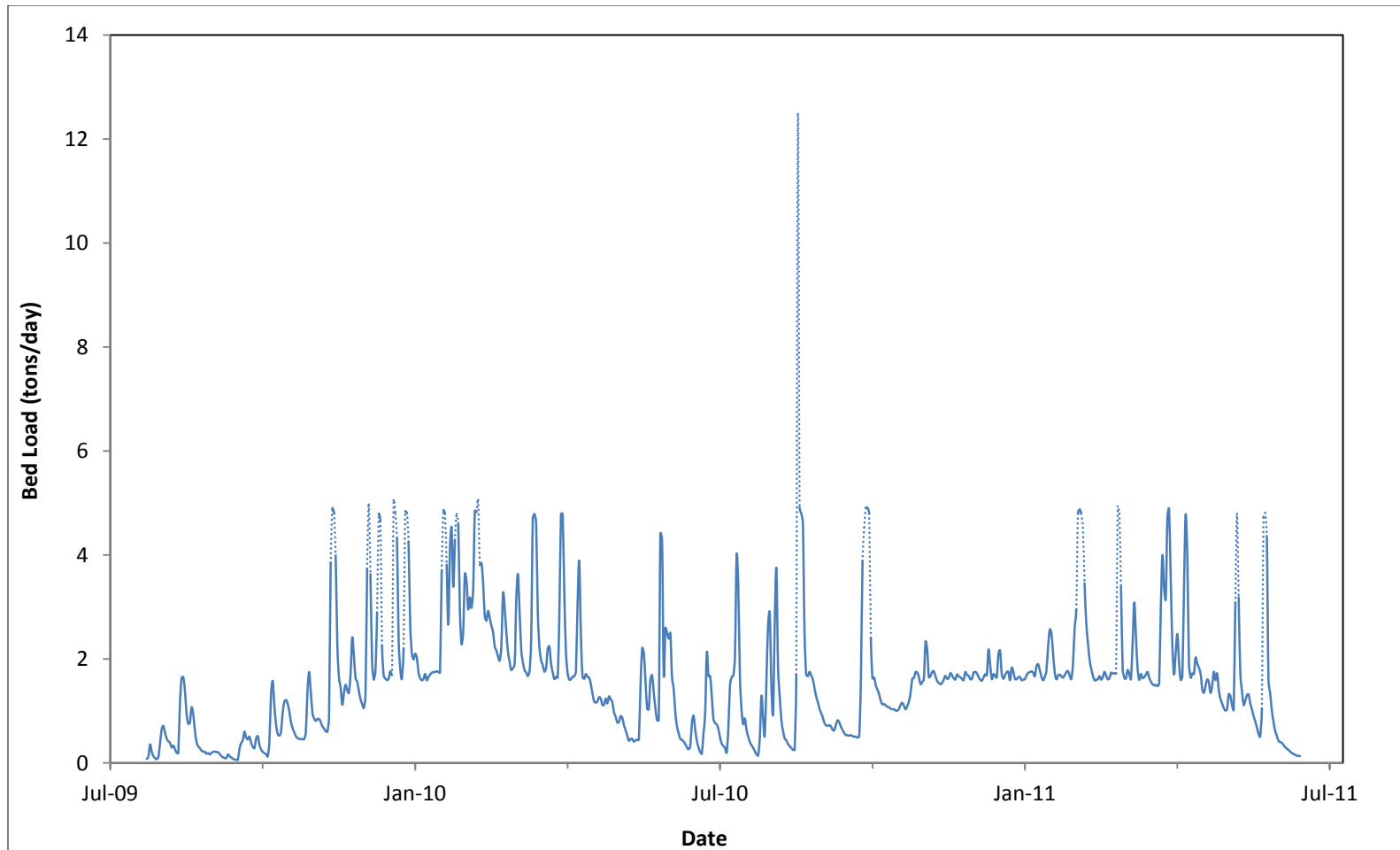


Figure C6-7: Sediment flux (tons/day) based upon daily flow averages of Juniper Creek (DNR). The solid lines are calculated from flow rates within the cross section surveyed while the dotted lines are based upon projected flow rates that exceed the boundaries of the channel survey.

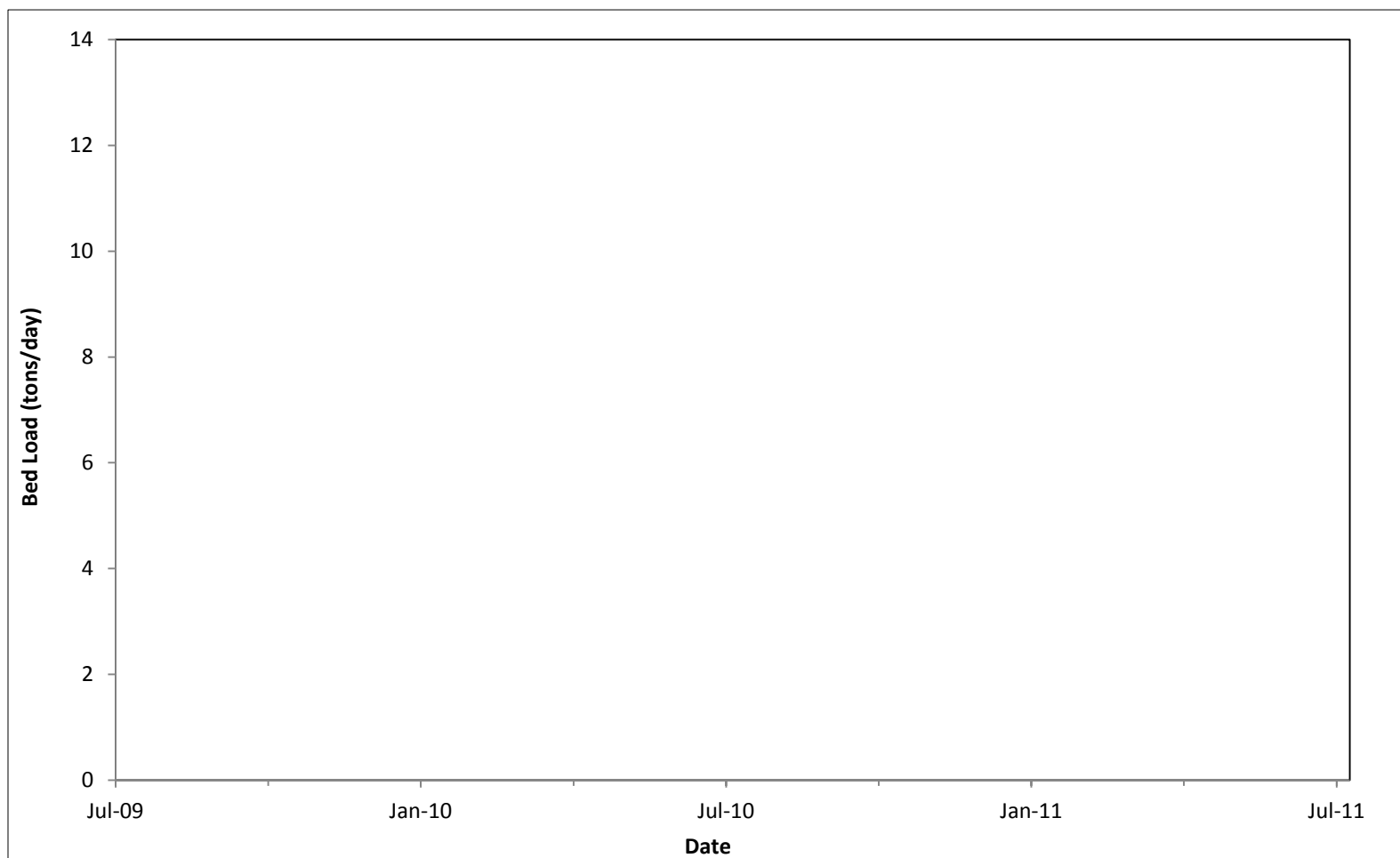


Figure C6-8: Sediment flux (tons/day) based upon daily flow averages of Jeffries Creek (USGS). This could not be calculated due to uncertainty of flow rate in this stream and the connection between a given flow and stage, which is pivotal in calculation of a manning's n , a measure used in the calculation of bed load.

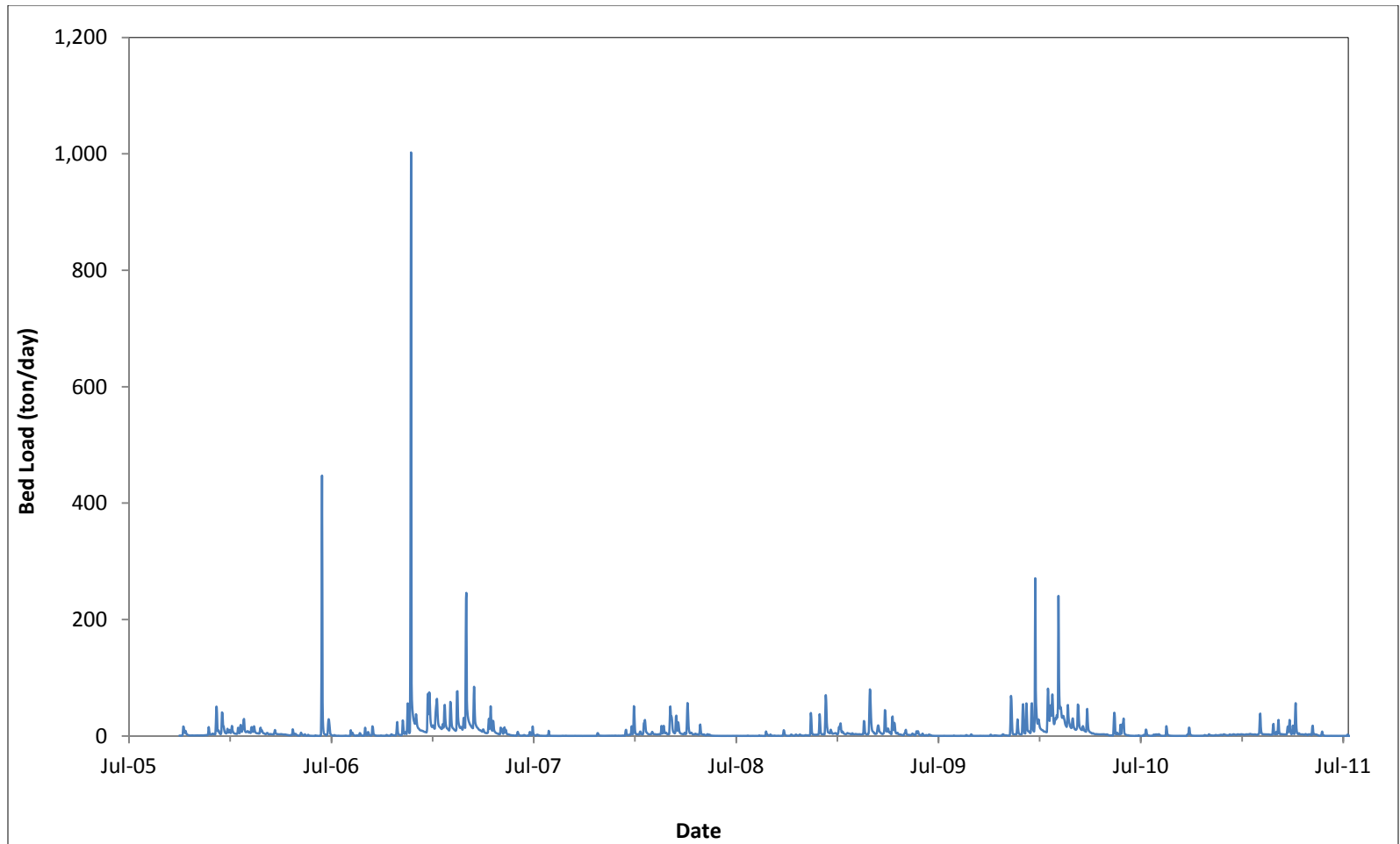


Figure C6-9: Sediment flux (tons/day) based upon daily flow averages of Black Creek near Chesterfield (USGS).

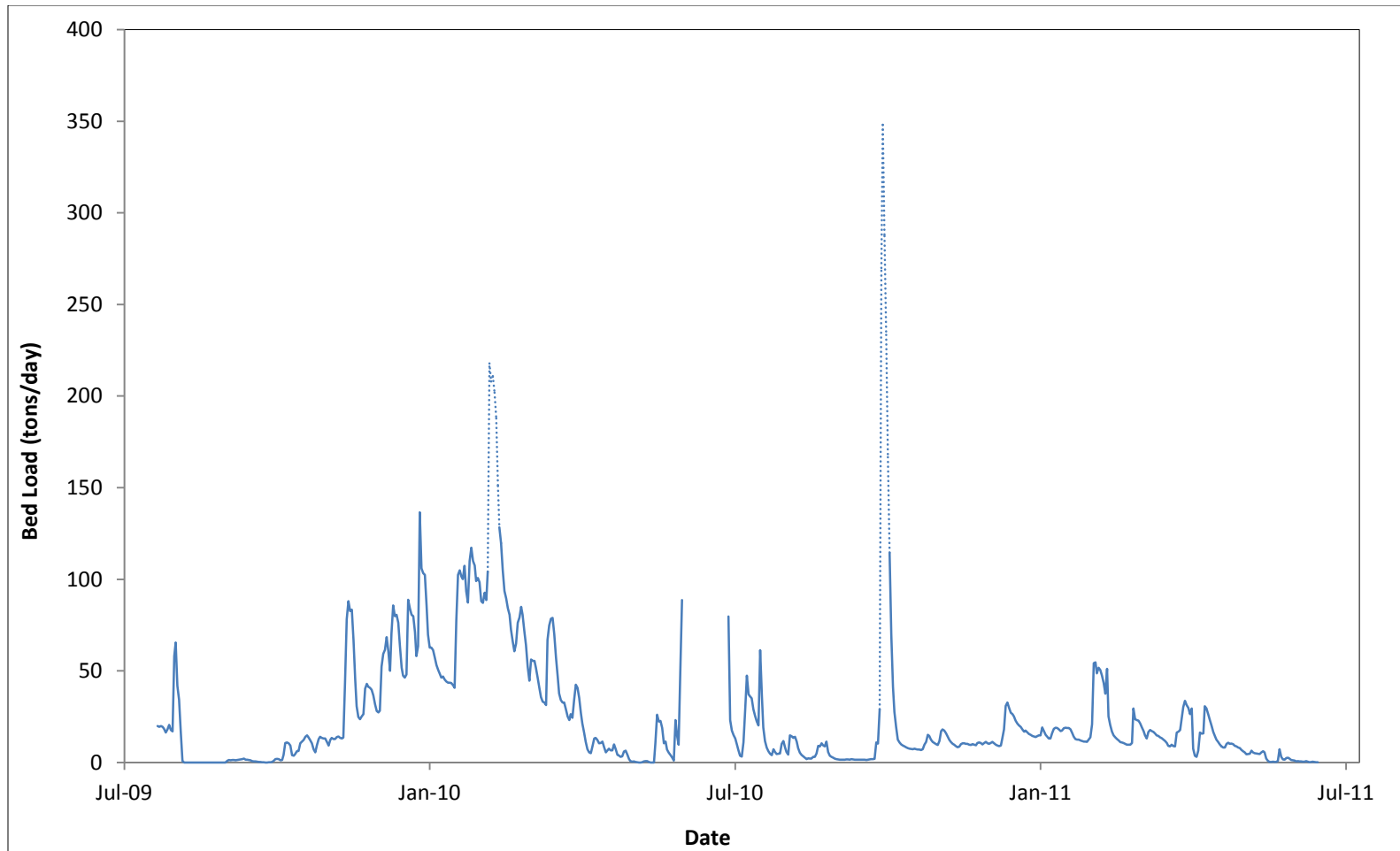


Figure C6-10: Sediment flux (tons/day) based upon daily flow averages Crooked Creek. The solid lines are calculated from flow rates within the cross section surveyed while the dotted lines are based upon projected flow rates that exceed the boundaries of the channel survey.

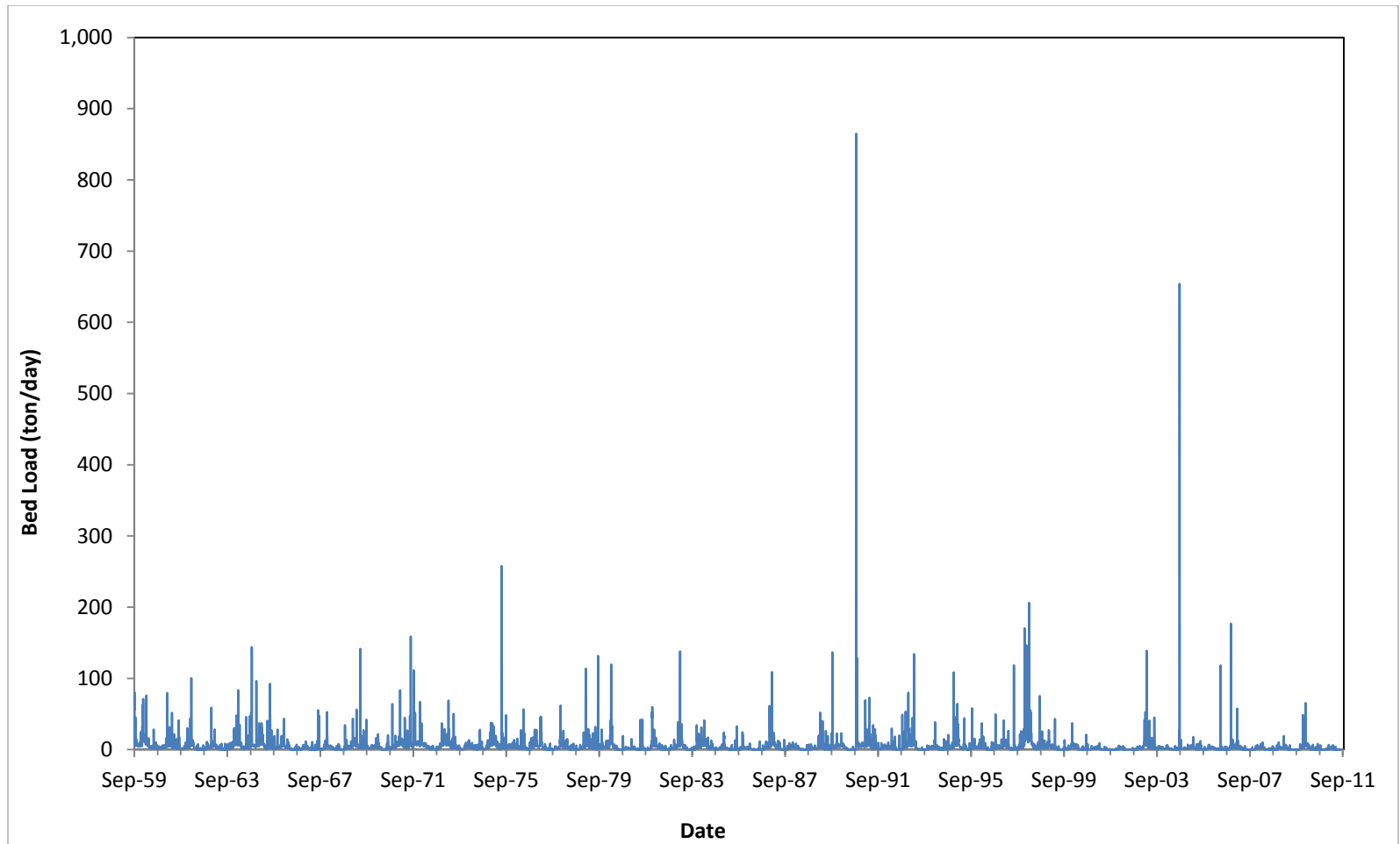


Figure C6-11: Sediment flux (tons/day) based upon daily flow averages of Black Creek near McBee (USGS).

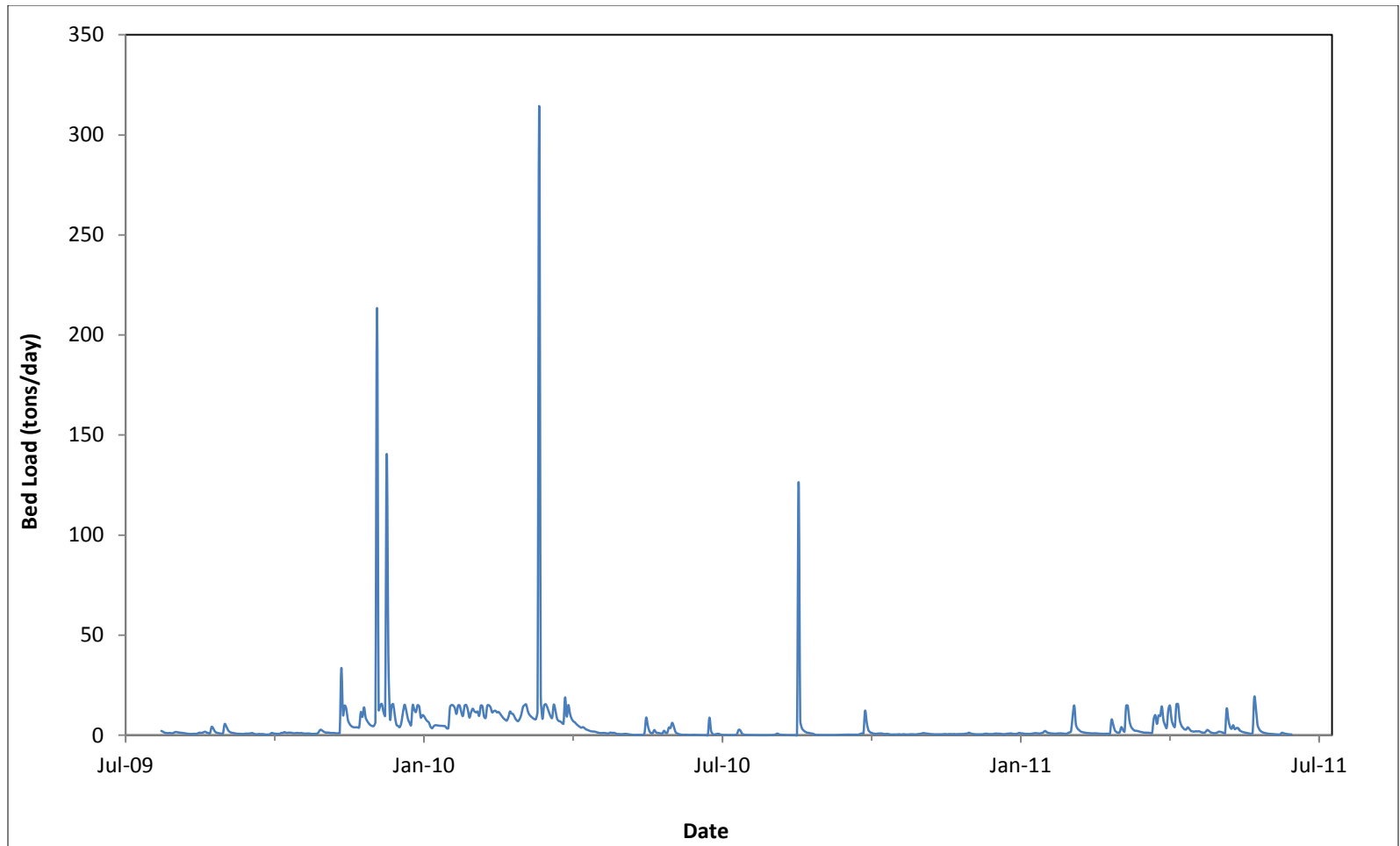


Figure C6-12: Sediment flux (tons/day) based upon daily flow averages of Thompson Creek.

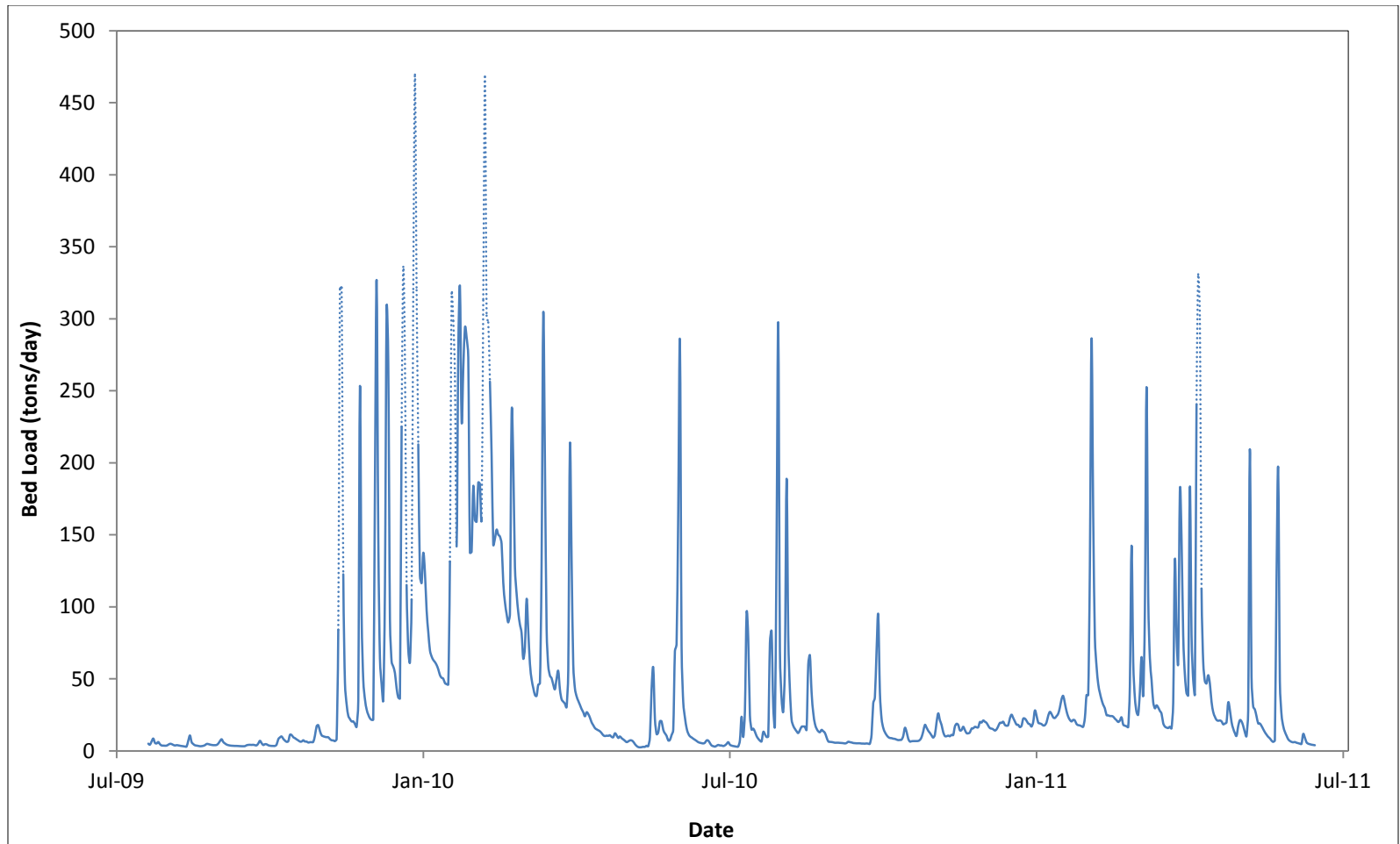


Figure C6-13: Sediment flux (tons/day) based upon daily flow averages of Lynch River. The solid lines are calculated from flow rates within the cross section surveyed while the dotted lines are based upon projected flow rates that exceed the boundaries of the channel survey.

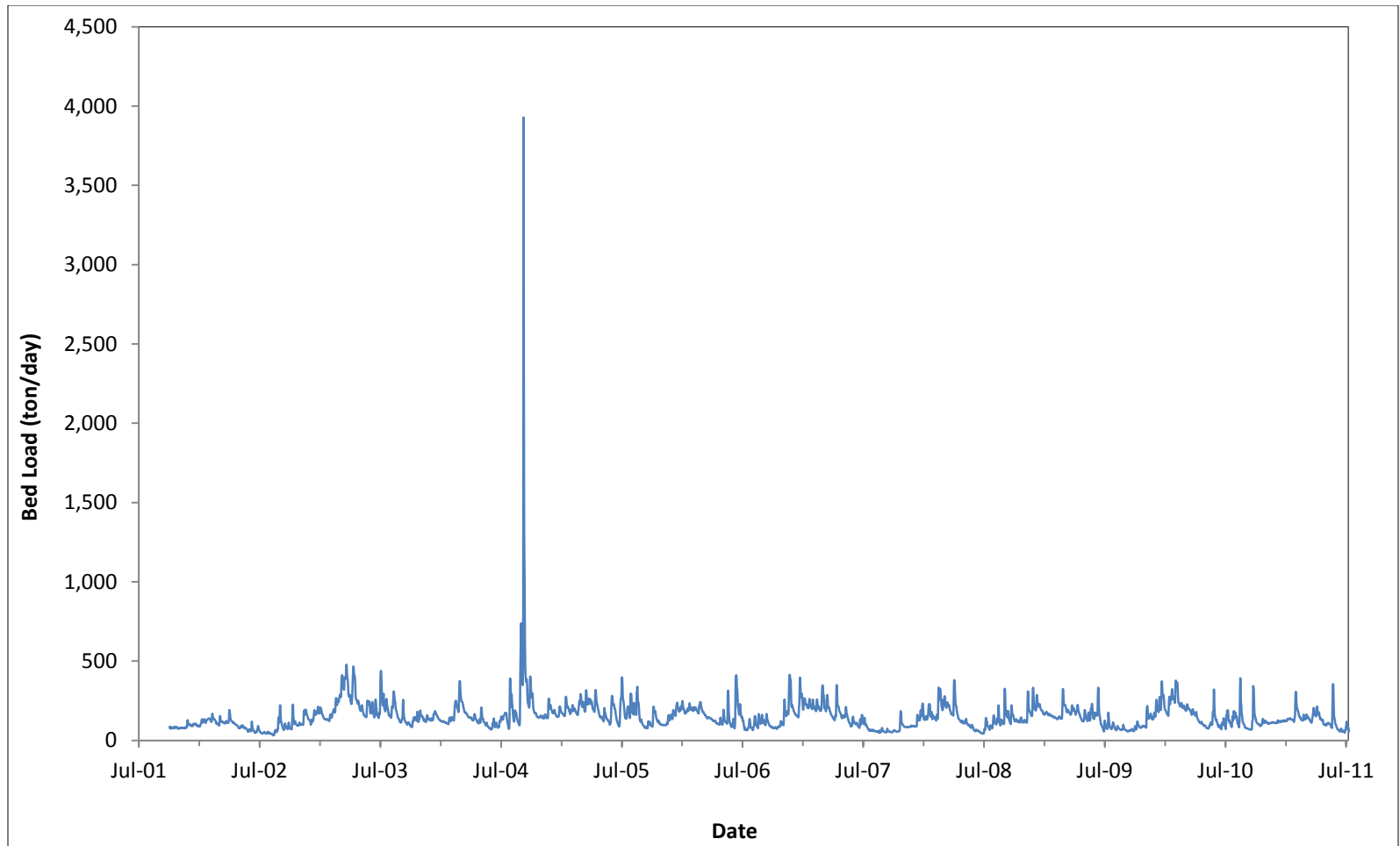


Figure C6-14: Sediment flux (tons/day) based upon daily flow averages of Black Creek near Quinby (USGS).

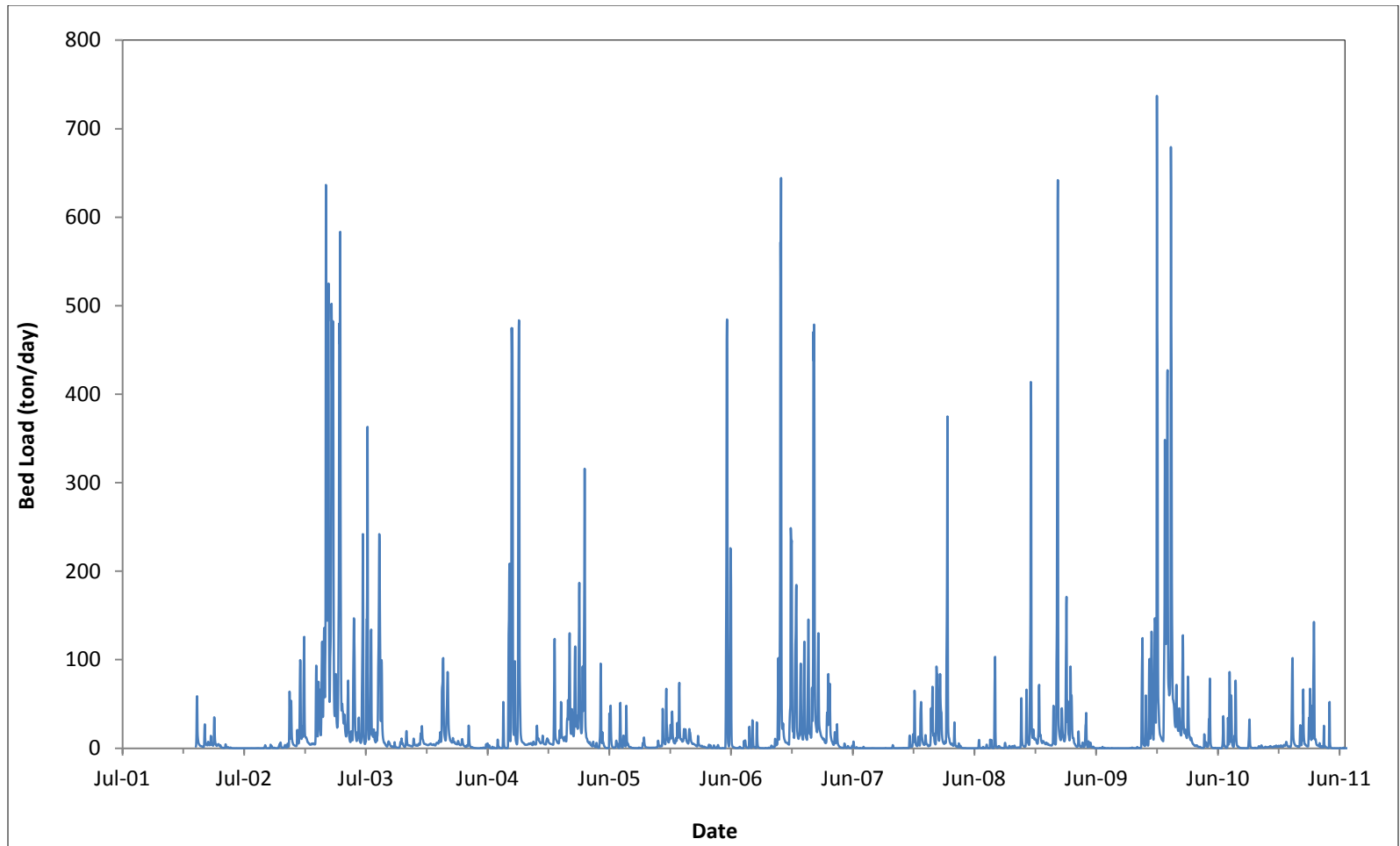


Figure C6-15: Sediment flux (tons/day) based upon daily flow averages of Lynch River near Bishopville (USGS).

REFERENCES

- Acreman, M. and M.J. Dunbar. 2004. Defining environmental river flow requirements – a review. *Hydrology and Earth System Sciences*, 8(5):861-876.
- Alexander, R.B., R.A. Smith, and G.E Schwartz. Effect of stream channel size on the delivery of nitrogen to the Gulf of Mexico. U.S. Geological Survey, 413 National Center, Reston, VA. *Nature* 403:758-761.
- Allan, J.D. 2004. Landscapes and Riverscapes: the influence of land use on stream ecosystems. *Annual Review of Ecology, Evolution, and Systematics* 35:257-284.
- Allan, J.D., D.L Erickson, and J. Fay. 1997. The influence of catchment land use on the stream integrity across multiple spatial scales. *Freshwater Biology* 37:149–161.
- Allan, J.D. and M.M. Castillo. 2007. *Stream Ecology: Structure and Function of Running Waters*. Springer, Dordrecht, The Netherlands.
- Allen, P.M., J.G. Arnold, and B.W. Byars. 1994. Downstream Channel Geometry for use in Planning-Level Models. *Water Resources Bulletin: American Water Resources Association*, 30(4):663-671.
- American Society of Civil Engineers (ASCE). 2006. *Sedimentation Engineering. Manuals and Reports of Engineering Practice*, No. 54. Vito A. Vanoni, ed., ISBN# 0784408238. Reston, VA.
- Anderson, C.S. 1995. Measuring and correcting for size selection in electrofishing mark–recapture experiments. *Transactions of the American Fisheries Society* 124:663–676.
- Andrews, E.D. 2011. Entrainment of gravel from naturally sorted riverbed material. *The Geological Society of America Bulletin* 1983(94):1225-1231.
- Arthington, A.H. and J.M. Zalucki. 1998. Comparative Evaluation of the Environmental Flow Assessment Techniques: Review of Methods. *LWRRDC Occasional Paper* 27/98.
- Arthington, A.H., S.E. Bunn, N.L. Poff and Robert J. Naiman. 2006. The challenge of providing environmental flow rules to sustain river ecosystems. *Ecological Applications*, 16(4):1311–1318.
- Arthington, A.H. 1998. Comparative Evaluation of the Environmental Flow Assessment Techniques: Review of Holistic Methodologies. *LWRRDC Occasional Paper* 26/98.
- Arthington, A.H. and R. Lloyd. 1998. Logan River Trial of the Building Block Methodology for Assessing Environmental Flow Requirements: Workshop Report. pp. 85. Center for Catchment and In-Stream Research, Griffith University and Department of Natural Resources, Brisbane.
- Arthington, A.H., J.M. King, J.H. O’Keeffe, S.E. Bunn, J.A. Day, B.J. Pusey, D.R. Blüdhorn and R. Tharme. 1992. Development of a holistic approach for assessing environmental flow requirements of riverine ecosystems. *Water Allocation for the Environment*. Eds J.J. Pigram and B. Hooper. pp. 69–76. Centre for Water Policy Research, University of New England: Armidale.
- Bachand, P.A.M., and A.J. Horne. 2000. Denitrification in constructed free-water surface wetlands: II. Effects of vegetation and temperature. *Ecological Engineering* 14:17-32.
- Baker, D.B., R.P. Richards, T.T. Loftus, and J.W. Kramer. 2004. A New Flashiness Index: Characterizations and Application to Midwestern Rivers and Streams. *Journal of the American Water Resources (JAWRA)* 40(2):503-522.

- Barker, I.C. and A. Kirmond. 1998. Managing surface water abstraction. *Hydrology in a Changing Environment* 1: 249-258.
- Bedoya, D., V. Novotny, and E.S. Manolagos. 2009. Instream and offstream environmental conditions and stream biotic integrity Importance of scale and site similarities for learning and prediction. *Ecological Modeling* 220: 2393- 2406.
- Berkman, H.E. and C.F. Rabeni. 1987. Effect of siltation on stream fish communities. *Environmental Biology of Fishes* 18(4):285-294.
- Blann, K.L., Anderson, J.L., Sands, G.R. and B. Vondracek. 2009. Effects of Agricultural Drainage on Aquatic Ecosystems: A Review. *Critical Reviews in Environmental Science and Technology*, 39(11):909-1001
- Bluhdorn, D.R. and A.H. Arthington. 1995. The utility of stream salinity models in the integrated management of Australian rivers. *The Ecological Basis for River Management*. pp. 115-123. John Wiley and Sons Ltd, London.
- Booth, D.B. and C.R. Jackson. 1997. Urbanization of Aquatic Systems: Degradation Thresholds, Stormwater Detection, and the Limits of Mitigation. *Journal of the American Water Resources Association (JAWRA)* 33(5):1077-1090
- Booth, D.B., J.R. Karr, S. Schaumann, C.P. Konrad, S.A. Morley, M.G. Larson, and S.J. Burges. 2004. Reviving Urban Streams: Land Use, Hydrology, Biology, and Human Behavior. *Journal of American Water Resources Association* 40(5): 1351-1384.
- Brabec, E.A. 2009. Imperviousness and Land-Use Policy: Toward an Effective Approach to Watershed Planning. *Journal of Hydraulic Engineering*, 14(4):425-433.
- Brabec, E.A., S. Schulte, and P.L. Richards. 2002. Impervious Surfaces and Water Quality: A Review of Current Literature and Its Implications for Watershed Planning. *Journal of Planning Literature*, 16(4):499-514.
- Brandt, S.A. 2000. Classification of geomorphological effects downstream of dams. *CATENA*, 40(4):375-401.
- Bray, D.I. 1972. Generalized regime-type analysis of Alberta Rivers. PhD thesis, University of Alberta, Edmonton, Canada.
- Brierley, G., H. Reid, K. Fryirs, and N. Trahan. 2010. What are we monitoring and why? Using geomorphic principles to frame eco-hydrological assessments of river condition. *Science of the Total Environment* 408:2025–2033.
- Brizga, S.O. 1998. Methods addressing flow requirements for geomorphological purposes. *Comparative Evaluation of Environmental Flow Assessment Techniques: Review of Methods*. (pp. 8-46). LWRRDC Occasional Paper No. 27/98.
- Brownlie, W.R. 1981. Prediction of flow depth and sediment discharge in open channels. Report No. KH-R-43A. California Inst. of Tech. W.M. Keck Lab. of Hydrology and Water Resources. Pasadena, CA.
- Buettiker, B. 1992. Electrofishing results corrected by selectivity functions in stock size estimates of brown trout (*Salmo trutta* L.) in brooks. *Journal of Fish Biology* 41:673–684.
- Bunn, S.E. and P.M. Davies. 2000. Biological processes in running waters and their implications for the assessment of ecological integrity. *Hydrobiologia* 422/423: 61-70.

- Castro, J.M. and P.L. Jackson. 2001. Bankfull discharge recurrence intervals and regional hydraulic geometry relationships: patterns in the Pacific Northwest, USA. *Journal of American Water Resources Association*, 37(5):1249-1262.
- Cavendish, M.G. and M.I. Duncan. 1986. Use of Instream Flow Incremental Methodology: a tool for negotiation. *Environmental Impact Assessment Review* 1986(6):347-363.
- Chang, H. H. 1988. *Fluvial Processes in River Engineering*. Krieger Publication Co., Melbourne, Florida.
- Changnon, S.A. and M. Demissie. 1996. Detection of changes in streamflow and floods resulting from climate fluctuations and land use-drainage changes. *Climatic Change*, 32(4):411-421.
- Chien, N. 1985. Changes in river regime after the construction of upstream reservoirs. *Earth Surface Processes and Landforms*, 10:143–159.
- Chow, V.T.. 1959. *Open-channel Hydraulics*. McGraw-Hill, New York. pp. 680.
- Cimbala, J.M. and Y.A. Cengel. 2008. *Essentials of Fluid Mechanics: Fundamentals and Applications*. McGraw Hill, United States.
- Cinotto, P.J. 2003. Development of Regional Curves of Bankfull-Channel Geometry and Discharge for Streams in the Non-Urban, Piedmont Physiographic Province, Pennsylvania and Maryland. US Geological Survey. Water-Resources Investigations Report 03-4014.
- Clark J.S., D.M. Rizzo, M.C. Watzin, and W.C. Hession. 2008. Spatial Distribution and geomorphic condition of fish habitat in streams: An analysis using hydraulic modeling and geostatistics. *River Research and Applications* 24: 885-899.
- Committee on Riparian Zone Functioning and Strategies for Management, Water Science and Technology Board, National Research Council. 2002. *Riparian Areas: Functions and Strategies for Management*. The National Academies Press. Washington, D.C. 20001.
- Cooksey, R.W. 1996. Review of the 'Expert Panel' process as a mechanism for determining environmental flows. Centre for Water Policy Research, University of New England, Armidale.
- Copeland, R.R. 1994. Application of Channel Stability Methods – Case Studies. US Army Corps of Engineers Flood Control Channels Research Program Technical Report HL-94-11.
- D'Ambrosio, J.L., L. R. Williams, J.D. Witter, and A. Ward. 2009. Effects of geomorphology, habitat and spatial location on fish assemblages in a watershed in Ohio, USA. *Environmental Monitoring Assessment*. 148:325-341.
- Dade, W.B. and P.F. Friend. 1998. Sediment Transport Regime, and Channel Slope in Alluvial Rivers. *The Journal of Geology*, 106(6):661-676.
- Davies, N.M., R.H. Norris, and M.C. Thoms. 2000. Prediction and assessment of local stream habitat features using large-scale catchment characteristics. *Freshwater Biology* 45(3):343-369
- Dejong, T.M. 1975. A Comparison of Three Diversity Indices Based on Their Components of Richness and Evenness. *OIKOS* 26(2):222-227.
- Dickman, M.. 1968. Some Indices of Diversity. *Ecology* 49(6):1191-1193
- Dolan, C. R. and L E. Miranda. 2003. Immobilization Thresholds of Electrofishing Relative to Fish Size. *Transactions of the American Fisheries Society* 132:969–976.

- Doll, B.A., D.E. Wise-Frederick, C.M. Buckner, S.D. Wilkerson, W.A. Harmon, R.E. Smith, and J. Spooner. 2002. Hydraulic Geometry Relationships for Urban Streams throughout the Piedmont of North Carolina. *Journal of American Water Resources Association* 38(3):641-651.
- Dudley, S.J., J.C. Fishenich, and S.R. Abt. 1998. Effect of Woody Debris Entrapment on Flow Resistance. *Journal of the American Water Resources Association* 34(5):1189-1197.
- Dunne, T. and L.B. Leopold. 1978. *Water in Environmental Planning*. W.H. Freeman and Company, San Francisco, California
- Elliot, C.R.N., M.J. Dunbar, I. Growing, M.C. Acreman. 1999. A habitat assessment approach to the management of groundwater dominated rivers. *Hydrological Processes* 1(3):459-475.
- Extence, C., D.M. Balbi, and R.P. Chadd. 1999. River flow indexing using British benthic macroinvertebrates: a framework for setting hydro-ecological objectives. *Regulated Rivers* 15:543-574.
- Fausch, K.D., J.R. Karr, and P.R. Yant. 1984. Regional Application of an Index of Biotic Integrity Based on Stream Fish Communities. *Transaction of the American Fisheries Society* 113:39-55.
- Fisher, J., and M.C. Acreman. 2004 Wetland nutrient removal: a review of evidence. *Hydrology and Earth System Sciences* 8(4):673-685.
- Fisher, R.A., A.S. Corbet and C.B. Williams. 1943., The relation between the number of species and the number of individuals in a random sample of an animal population. *Journal of Animal Ecology* 12:42-58.
- Fitzpatrick, F.A., B.C. Scudder, B.N. Lenz, and D.J. Sullivan. 2001. Effects of multi-scale environmental characteristics on agricultural stream biota in eastern Wisconsin. *Journal of the American Water Resources Association* 37(6):1489-1507.
- Fongers, D., K. Manning, and J. Rathbun. 2007. Application of the Richards-Baker Flashiness Index to Gaged Michigan Rivers and Streams. DEQ. Michigan's Nonpoint Source Program.
- Frimpong, E.A., T. M. Sutton, B.A. Engel, and T.P. Simon. 2005. Spatial-Scale Effects on Relative Importance of Physical Habitat Predictors of Stream Health. *Environmental Management* 36(6):899-917.
- Gauckler, P. 1867. Etudes Théoriques et Pratiques sur l'Ecoulement et le Mouvement des Eaux, *Comptes Rendues de l'Académie des Sciences, Paris, France, Tome 64*, pp. 818-822
- Gedan, K.B., M.L. Kirwin, E. Wolanski, E.B. Barbier, and B.R. Silliman. 2010. The present and future role of coastal wetland vegetation in protecting shorelines: answering recent challenges to a paradigm. *Climatic Change* 106: 7-29.
- Gergel, S.E., M.G. Turner, J.R. Miller, J.M. Melack, and E.H. Stanley. 2002. Landscape indicators of human impacts to riverine systems. *Aquatic Science* 64:118-128.
- Gippel, C.J. and M.J. Stewardson. 1998. Use of Wetted Perimeter in Defining Minimum Environmental Flows. *Regulated Rivers: Research and Management* 14:53-67
- Gleason, A. 1922. On the relation between species and area. *Ecological Society of America*, 3(2):158-162.
- Gordon, N.D. 2004. *Stream Hydrology: An Introduction for Ecologists*. John Wiley and Sons, 2004.
- Gordon, N.D., T.A. McMahon and B.L. Finlayson. 1992. *Stream Hydrology: An Introduction for Ecologists*. John Wiley and Sons, Brisbane.

- Graf, W.L. 1975. The impact of suburbanization on fluvial geomorphology: *Water Resources Research*, 11:690-692.
- Gurnell, A.M. 1998. The hydrogeomorphological effects of beaver dam-building activity. *Progress in Physical Geography* 22(2):167-189.
- Haan, C.T., B.J. Barfield, and J.C. Hayes. 1994. *Design Hydrology and Sedimentology for Small Catchments*. Academic Press, Inc. San Diego, California.
- Hack J.T. and J.C. Goodlett. 1960. Geomorphology and forest ecology of mountain region in the central Appalachians. U.S. Geological Survey Professional Paper 347.
- Hammer, T.R. 1972. Stream Channel Enlargement Due to Urbanization. *Water Resources Research* 8(6):1530-1540.
- Harding, J.S., E.F. Benfield, P.V. Bolstad, G.S. Helfman, and E.D.D. Jones III. 1998. Stream biodiversity: The ghost of land use past. *Proc. Natl. Acad. Sci. USA*, 95:14843-14847.
- Harrelson, C.C., C.L. Rawlins, and J.P. Potyondy. 1994. *Stream Channel Reference Sites: An Illustrated Guide to Field Technique*. Fisheries Stream Survey Manual, USDA Forest Service, Rocky Mountain Research Service.
- Hey, R.D. and C.R. Thorne. 1986. Stable Channels with Mobile Gravel Beds. *Journal of Hydraulic Engineering* 112(8): 671-689.
- Hicks, A.L. and J.S. Larson. 1997. Impacts of urban stormwater runoff on freshwater wetlands and the role of aquatic invertebrate bioassessment. Effects of watershed development and management on aquatic ecosystems, L. A. Roesner, ed., ASCE, New York, pp. 386– 401.
- Hillman, G.R. 1998. Flood Wave Attenuation by a Wetland Following a Beaver Dam Failure on a Second Order Boreal Stream. *Wetlands* 18(1):21-34.
- Hobbs, R.J. and J.A. Harris. 2001. Restoration Ecology: Repairing the Earth's Ecosystems in the New Millennium. *Restoration Ecology* 9(2):239-246.
- Hrodey, P.J., T.M. Sutton, E.A. Frimpong, and T.P. Simon. 2009. Land-use Impacts on Watershed Health and Integrity in Indiana Warmwater Streams. *The American Midland Naturalist* 161(1): 76-95.
- Hughes, D.A. and P. Hannart. 2003. A desktop model used to provide an initial estimate of the ecological instream flow requirements of rivers in South Africa. *Journal of Hydrology*, 270(3-4):167-181.
- Hughes, R.M., S.A. Heiskary, W.J. Matthews, and C.O. Yoder. 1994. Use of ecoregions in biological monitoring. Biological monitoring of aquatic systems. pp. 125–151. Edited by S.L. Loeb and A. Spacie. Lewis Publishers, Boca Raton, Fla.
- Huston, M.A. 1998. *Biological Diversity: The Coexistence of Species on Changing Landscapes*. Cambridge: Cambridge University Press.
- Jayakaran, A.D., D. Mecklenburg, A.D. Ward, L. Brown, and A. Weekes. 2005. Formation of Fluvial Benches in Headwater Channels in the Midwestern Region of the USA. *International Agricultural Engineering Journal* 14(4):193-208.
- Jayakaran, A.D. and A.D. Ward. 2007. Geometry of inset channels and the sediment composition of fluvial benches in agricultural drainage systems in Ohio. *Journal of Soil and Water Conservation* 62(4):296-307.

- Jayakaran, A.D., D.E. Mecklenburg, J.D. Witter, A.D. Ward, and G.E. Powell. 2010. Fluvial processes in agricultural ditches in the North Central Region of the United States and implications for their management. *Agricultural Drainage Ditches: Mitigation Wetlands for the 21st Century*, 2010: 195-221 ISBN: 978-81-308-0376-0 Editors: Matthew T. Moore and Robert Kröger.
- Jing, Shuh-Ren, Yin-Feng Lin, Der-Yuan Lee, and Tse-Wen Wang. 2001. Nutrient removal from polluted water by using constructed wetlands. *Bioresource Technology* 76:131-135.
- John, F. 2001. Standard Operating Procedure for Streamflow Measurement. US EPA, Region 6. Dallas, Texas.
- Johnson, P.A. and T.M. Heil. 1996. Uncertainty in Estimating Bankfull Conditions. *Water Resources Bulletin, American Water Resources Association* 32(6):1283-1291.
- Jones, C.G., J.H. Lawton, and M. Shachak. 1997. Positive and negative effects of organisms as physical ecosystem engineers. *Ecology* 78(7):1946-1957.
- Jones, K.B., A.C. Neale, M.S. Nash, R.D. Van Remortel, J.D. Wickham, K.H. Ritters, and R.V. O'Neil. 2001. Predicting nutrient and sediment loadings to streams from landscape metrics: A multiple watershed study from the United States Mid-Atlantic Region. *Landscape Ecology*, 16:301-312
- Julien, Y.P. and J. Wargadalam. 1995. Alluvial Channel Geometry: Theory and Applications. *Journal of Hydraulic Engineering* 121:312-325
- Kaufman, P.R. and R.M. Hughes. 2006. Geomorphic and Anthropogenic Influences on Fish and Amphibians in Pacific Northwest Coastal Streams. *American Fisheries Society Symposium* 48:429-455.
- Kavanagh, B. F. and Glenn Bird, S. J. (1996). *Surveying principles and applications* (4 ed.). Prentice Hall. pp. 257-264. ISBN 0-13-438300-1.
- Khatsuria, R.M. 2010. How and why rivers meander. Central Water and Power Research Station, Pune, India.
- King, J. and D. Louw. 1998. Instream flow assessments for regulated rivers in South Africa using the Building Block Methodology. *Aquatic Ecosystem Health and Management* 1(2):109-124.
- King, J.M. and R.E. Tharme. 1994. Assessment of the Instream Flow Incremental Methodology and the Initial Development of the Alternative Instream Flow Methodologies for South Africa. Report to the Water Research Commission, Contract Number K5/259. Pretoria, South Africa.
- Klein, R. D. 1979. Urbanization and Stream Quality Impairment. *JAWRA Journal of the American Water Resources Association (JAWRA)* 15:948-963.
- Knighton, A .D. 1980. Longitudinal changes in size and sorting of stream-bed material I four English rivers. *Geological Society of America Bulletin* 91:55-62.
- Kondolf, G.M. 1997. Hungry water: effects of dams and gravel mining on river channels. *Environ. Mgmt* 21(4):533-551.
- Kratzer, E.B. and D.P. Batzer. Spatial and Temporal Variation in the Aquatic Macroinvertebrates in the Okefenokee Swamp, Georgia, USA. *Wetlands*, 27(1):127-140.
- Lai, Chan-Ji, Chang-Ling Liu, and Yeu-Zen Lin. 2000. Experiments on Flood-Wave Propagation in Compound Channel. *Journal of Hydraulic Engineering*, 126(7):492-501.

- Lammert, M. and J.D. Allan. 1999. Assessing Biotic Integrity of Streams: Effects of Scale in Measuring the Influence of Land Use/Cover and Habitat Structure on Fish and Macroinvertebrates. *Environmental Management* 23(2):257-270.
- Lamoureux, N. and H. Capra. 2002. Simple predictions of instream habitat model outputs for target fish populations. *Freshwater Biology* 47(8):1543-1556.
- Landres, P.B., R.L. Knight, S.T.A. Pickett, and M.L. Cadenasso. 1998. *Ecological Effects of Administrative Boundaries*. Island Press.
- Lecraw, R. and R. Mackereth. 2010. Sources of small-scale variation in the invertebrate communities of headwater streams. *Freshwater Biology* 55, 1219-1233.
- Leopold, L.B. 1992. Sediment Size that Determines Channel Morphology. *Dynamics of Gravel-bed Rivers*. pp 297-311.
- Leopold, L.B. 1994. *A View of the River*. President and Fellows at Harvard College, United States, ISBN: 0-674-93732-5.
- Leopold, L.B. 1973. River Channel Change with Time: An Example. *Bulletin of the Geological Society of America Bull. Geol. Soc. Am* 84(6):1845-1860. Jun 1973.
- Leopold, L.B. 1968. *Hydrology for Urban Planning - A Guidebook on the Hydrologic Effects of Urban Use*. US Geological Survey, Washington, D.C.
- Leopold, L. B., and M.G. Wolman. 1957. River channel patterns—braided, meandering, and straight: U. S. Geol. Survey Prof. Paper 282B, p. 39-85.
- Limerinos, J.T., 1970. Determination of the Manning coefficient from measured bed roughness in natural channels. US Geological Survey Water-Supply Paper 1898-B. pp. 47.
- Maddock, I. 1999. The importance of physical habitat assessment for evaluating river health. *Freshwater Biology* 41:373–391.
- Magurran, A.E. and Dawn A. Phillip, 2001. Implications of Species Loss in Freshwater Fish Assemblages. *Ecography*, 24(6):645-650.
- Marcus, W.A., K. Roberts, L. Harvey, and G. Tackman. 1992. An evaluation of methods for estimating manning's n in small mountain streams. *Mountain Research and Development* 12(3):227-239.
- Marshall, S. and M. Elliot. 1998. Environmental Influences on the Fish Assemblage of Humber Estuary, U.K. *Estuarine, Coastal, and Shelf Science* 46:175-184.
- Matthews, W.J. 1998. *Patterns in freshwater fish ecology*. Kluwer Academic Publishers, Norwell Massachusetts.
- Matthews, R.C. and Y. Bao. 1991. The Texas Method of Preliminary Instream Flow Determination. *Rivers* 2:295-310.
- Maxwell, J.R., C.E. Edwards, M.E. Jensen, S.J. Paustian, H. Parrot, and D.M. Hill. 1995. A hierarchical framework of aquatic ecological units in North America. U.S. Dept. of Agric., Forest Service.
- McCosker, R.O. 1997. Environmental flows for riparian vegetation. *Water for the Environment: Recent Approaches to Assessing and Providing Environmental Flows*. pp. 75-82. Brisbane, Australia.

- McCune, B. and J.B. Grace. 2002. *Analysis of Ecological Communities*. Duke University, Chappel Hill, North Carolina.
- McIntosh, R.P. 1967. An index of diversity and the relation of certain concepts to diversity. *Ecology* 48: 392-404.
- Mellroy, S.K., C. Montagne, C.A. Jones, and B.L. McGlynn. 2008. Identifying Linkages Between Land Use, Geomorphology, and Aquatic Habitat in a Mixed-Use Watershed. *Environmental Management* 42:867-876
- McRae, S.E., J.D. Allan, and J.B. Burch. 2004. Reach-and-catchment-scale determinants of distribution of freshwater mussels (Bivalvia: Unionidae) in southeastern Michigan, U.S.A. *Freshwater Biology* 49:127–142.
- McCune, B. and J.B. Grace, 2002. *Analysis of ecological communities*. MjM Sofwre Design, Gleneden Beach, OR, US.
- Mecklenburg D.E. and A.D. Ward. 2004. STREAM modules: spreadsheet tools for river evaluation, assessment and monitoring. ASAE Publication Number 701P0904.
- Menhinick, E.F. 1964. A Comparison of Stone Species-Individuals Diversity Indices Applied to Samples of Field Insects. *Ecological Society of America* 45(4):859-861.
- Metcalf, C.K., S.D. Wilkerson, and W.A. Harmon. 2009. Bankfull Regional Curves for North and Northwest Florida Streams. *Journal of American Water Resources Association (JAWRA)* 45(5):1260-1272.
- Montgomery, D.R. and J.M. Buffington. 1997. Channel-reach morphology in mountain drainage basins. *GSA Bulletin* 109(5):596-611.
- Morrison, M.M., B.G. Marcot, and R.W. Mannan, 2006. *Wildlife-Habitat Relationships: Concepts and Applications*. Island Press, Washington, D.C., pp. 493.
- Moscip, A.L. and Montgomery, D.R. 1997. Urbanization, Flood Frequency, and Salmon abundance in Puget Lowland Streams. *Journal of the American Water Resources Association (JAWRA)* 33(6): 1289–1297.
- Moyle, P.B., and B. Herbold. 1987. Life-history patterns and community structure in stream fishes of western North America: comparisons with eastern North America and Europe. Pages 25-32 in W. J. Matthews and D. C. Heins, eds. *Community and Evolutionary Ecology of North American Stream Fishes*. University of Oklahoma Press, Norman, OK.
- Nakano, T., S. Kuniyoshi, and M. Fukuda. 2000. Temporal variation in methane emission from tundra wetlands in a permafrost area, northeastern Siberia. *Atmospheric Environment* 34:1205-1213.
- Naiman, R.J., C.A. Johnston, and J.C. Kelley. 1988. Alteration of North American Streams by Beaver. *BioScience*, Vol. 38(11):753-762.
- NOAA. Glossary of Hydrologic Terms.
http://www.nws.noaa.gov/om/hod/SHManual/SHMan014_glossary.htm
- Natural Resource Conservation Service. 2007. NRCS Stream Restoration Design Handbook. USDA, NRCS NEH-654.
- Nichols, D.S. 1983. Capacity of Natural Wetlands to Remove Nutrients from Wastewater. *Journal of the Water Pollution Control Federation* 55(5):495-505.

- Nicholson, M.D. and S. Jennings. 2004. Testing candidate indicators to support ecosystem-based management: the power of monitoring surveys to detect temporal trends in fish community metrics. *ICES Journal of Marine Science* 64(1):35-42.
- Nixon MA. 1959. Study on the bank-full discharges of rivers in England and Wales. *Proceedings of the Institute of Civil Engineers* 12:157-174.
- Olsen, D.S, A.C. Whitiker, and D.F. Potts. 1997. Assessing stream channel stability thresholds using flow competence estimates at bankfull stage. *Journal of the American Water Resources Association* 33(6):1197-1207.
- Olsen, D.M., E. Dinerstein, E.D. Wikramanayake, N.D. Burgess, G.V.N. Powell, E.C. Underwood, J.A. D'amico, I. Itoua, H.E. Strand, J.C. Morrison, C.J. Loucks, T.F. Allnutt, T.H. Ricketts, Y. Kura, J.F. Lamoreux, W.W. Wettengel, P. Hedao, and K.R. Kassem. 2001. Terrestrial Ecoregions of the World: A New Map of Life on Earth. *BioScience*, 51(11):933-938. 2001.
- Omernik, J.M., A.R. Abernathy, and L.M. Male. 1981. Stream nutrient levels and proximity of agricultural and forest land to streams: some relationships. *Journal of Soil and Water Conservation* 36:227-231.
- Orth, D.J. and O.E. Maughan. 1982. Evaluation of the Incremental Methodology for Recommending Instream Flows for Fishes. *Transaction of the America Fishery Society* 111:413-445.
- Osborne, L.L. and M. J. Wiley, 1988. Empirical relationships between land use/land cover and stream water quality in an agricultural watershed. *Journal of Environmental Management* 26:9-27.
- Oswood, M.E., and W.E. Barber. 1982. Assessment of fish habitat in streams: Goals, constraints, and a new technique. *Fisheries* 7:8-11.
- Paller, M.H., M.J.M. Reichert, and John M. Dean. 1996. Use of Fish Communities to Assess Environmental Impacts in South Carolina Coastal Plain Streams. *Transactions of the American Fisheries Society*, 125: 633-644. Paola, Chris and Rebecca Seal. 1995. "Grain Size Patchiness as a Cause of Selective Deposition and Downstream Fining." *Water Resources Research*, 31(5):1395-1407.
- Paola, C., and Seal, R., 1995, Grain size patchiness as a cause of selective deposition and downstream fining: *Water Resources Res.*, v. 31, p. 1395-1407.
- Parasiewicz, P. and M.J Dunbar, Physical habitat modeling for fish: a developing approach. *Arch. Hydrobiol. Suppl.* 135(2-4):1-30.
- Piégay, H. and A.M. Gurnell. 1997. Large woody debris and river geomorphology pattern: examples from S.E France and S. England. *Geomorphology* 19:99-116.
- Pizzuto, J.E., W.C. Hession, and M. McBride. 2000. Comparing gravel-bed rivers in paired urban and rural catchments of southeastern Pennsylvania. *Geology* 28:79-82.
- Poff, N.L., J.D. Allan, M.B. Bain, J.R. Karr, K.L. Prestegard, B.D. Richter, R.E. Sparks, and J.C. Stromberg. 1997. The Natural Flow Regime: A paradigm for river conservation and restoration. *Bioscience* 47(11):269-784.
- Poff, N.L., B.D. Bledsoe, and C.O. Cuhacyan. 2006. Hydrologic variation with land use across the contiguous United States: geomorphic and ecological consequences for stream ecosystems. *Geomorphology* 79:264-285.
- Poff, N.L. and J.V. Ward. 1989. Implications of streamflow variability and predictability for lotic community structure: A regional analysis of streamflow patterns. *Aquatic Science*. 46:1805-1818.

- Poole, G.C. and C.H. Berman. 2001. An Ecological Perspective on In-Stream Temperature: Natural Heat Dynamics and Mechanisms of Human-Caused Degradation. *Environmental Management* 27(6):787-802.
- Powell, G.E., D.E. Mecklenburg, and A.D. Ward. 2006. Evaluating Channel-Forming Discharges: A Study of Large Rivers in Ohio. *ASABE Vol.* 49(1): 35-46.
- Prestegard K.L. 1988. Morphological controls on sediment delivery pathways. Walling DE, ed. *Sediment budgets*. Wallingford, UK: IAHS Press. International Association of Hydrological Sciences 174:533-540.
- Pusey, B.J. 1998. Methods addressing the flow requirements of fish. In *Comparative Evaluation of Environmental Flow Assessment: Review of Methods*. pp. 66-105. LWRRDC Occasional Paper no. 27/98.
- Radecki-Pawlik A. 2002. Bankfull Discharge in Mountain Streams: Theory and Practice. *Earth Surf. Process. Landforms* 27:115–123.
- Rankin, E.T. 1989. The Qualitative Habitat Evaluation Index [QHEI]: Rationale, Methods, and Application. State of Ohio Environmental Protection Agency, Ecological Assessment Section, Division of water Quality Planning and Assessment. Columbus, Ohio.
- Rankin, E.T. 1995. Habitat indices in water resource quality assessments. Pages 181–208 in W. S. Davis, and T. P. Simon (eds.), *Biological assessment and criteria*. Lewis Publishers, Boca Raton, Florida.
- Reeves, A. 1994. Urgent need for holistic approach to environmental flows. *Environmental Flows Seminar Proceedings*. pp. 163-169. AWWA Inc.
- Reinfelds, I., T. Haeusler, A.J. Brooks and S. Williams. 2004. Refinement of the wetted perimeter breakpoint method for setting cease-to-pump limits or minimum environmental flows. *River Research and Applications* 20:671-685.
- Reynolds, J.B. and D.E. Simpson. 1978. Evaluation of Fish Sampling and Rotenone Census. U.S. Fish and Wildlife Service, Missouri Department of Conservation and the University of Missouri-Columbia.
- Richards, C., R.J. Haro, L.B. Johnson, and G.E. Host. 1997. Catchment and reach-scale properties as indicators of macroinvertebrate species traits. *Freshwater Biology*, 37:219-230.
- Richards, C., L.B. Johnson, and G.E. Host. 1996. Landscape-scale influences on stream habitats and biota. *Fish and Aquatic Science* 53(1): 295-311.
- Richardson, B.A. 1986. Evaluation of instream flow methodologies for freshwater fish in New South Wales. In *Stream Protection: The Management of Rivers for Instream Uses*. Water Studies Centre, Chisholm Institute of Technology: Melbourne.
- Richter, B.D., R. Matthews, D.L. Harrison, and R. Wigington. 2003. Ecologically Sustainable Water Management: Managing River Flows for Ecological Integrity. *Ecological Applications*. The Nature Conservancy, Charlottesville, VA.
- Richter, B.D., J.V. Baumgartner, R. Wigington, and D.P. Braun. 1995. How much water does a river need? *Freshwater Biology* 37:231-249.
- Richter, B.D., J.V. Baumgartner, J. Powell, and D.P. Braun. 1996. A method for assessing hydrologic alteration within ecosystems. *Conservation Biology* 10:1163–1174.

- Rosgen, D.L. 1994. A classification of natural rivers. *Catena* 22(3):169.
- Roth, N.E., J.D. Allan, and D.L. Erickson. 1996. Landscape influences on stream biotic integrity assessed at multiple spatial scales. *Landscape Ecology* 11:141–156.
- Sanderson, L. 2009. Changes in fish diversity to hydrologic and suspended sediment variability in the Sandusky River, Ohio: a genetic programming approach. Submitted to the Graduate College of Bowling Green State University in partial fulfillment of the requirements for the degree of *Masters of Science*, August 2009.
- Scatena, F.N. 2003. A Survey of Methods for Setting Minimum Instream Flow Standards in the Caribbean Basin. International institute of Tropical Forestry, USDA Forest Service, San Juan, Puerto Rico, USA.
- Schiemer, F. 2000. Fish as indicators for the assessment of the ecological integrity of large rivers. *HydroBiologia*, 422-423(0):271-278.
- Schlosser, I.J. 1991. Stream Fish Ecology: A Landscape Perspective. *BioScience* 41(10):704-712.
- Schoonover, J.E., B.G. Lockaby, and B.S. Helms. 2006. Impacts of Land Cover on Stream Hydrology in the West Georgia Piedmont, USA. *Journal of Environmental Quality* 35: 2123-2131.
- Schueler, T.R. 1994. The Importance of Imperviousness. *Watershed Protection Techniques*, 1(3):100-111.
- Schumm, S.A. 2005. Patterns of Alluvial Rivers. *Annual Review of Earth and Planetary Sciences* 13:5-27.
- Schumm, S.A., M.D. Harvey, and C.C. Watson. 1984. Incised Channels: Morphology, Dynamics, and Control Littleton (CO): Water Resources Publications.
- Schumm, S.A., M.D. Harvey, and C.A. Watson. 1981. Yazoo Basin geomorphology. U.S. Dept. of Agric., Soil Conservation Service project SCS–23–MS– 80.
- Schumm, S.A. 1968. River adjustment to altered hydrologic regimen, Murrumbidgee River and paleochannels, Australia. US Govt. Print Off. Washington, D.C.
- Shannon, C.E., and W. Weaver. 1949. The mathematical theory of communication. Univ. Illinois Press, Urbana. pp. 117
- Shields, A. 1936 (in English). Anwendung der Aehnlichkeitsmechanik und der Turbulenzforschung auf die Geschiebebewegung [Application of similarity principles and turbulence research to bed-load movement]. Mitteilungen der Preußischen Versuchsanstalt für Wasserbau. 26. Berlin: Preußischen Versuchsanstalt für Wasserbau.
- Simon, A. 1989. A model of channel response in disturbed alluvial channels. *Earth surface processes and landforms* 14(1):11–26.
- Simpson, E. H. 1949. Measurement of diversity. *Nature* 163:688.
- Sophocleous, M. 2002. Interactions between groundwater and surface water: the state of the science. *Hydrogeology Journal* 10:52-67.
- Sponseller, R.A., E.F. Benfield, and H.M. Valett. 2001. Relationships between land use, spatial scale and stream macroinvertebrate communities. *Freshwater Biology* 46:1409-1424.

- Stalnaker, C., B.L. Lamb, J. Henriksen, K. Bovee, and J. Bartholow. 1995. The Instream Flow Methodology A Primer for IFIM. National Biological Service, US Department of Interior. Biological Report 29.
- Stalnaker, C.B. and S.C. Arnette. (Eds) 1976. Methodologies for the Determination of Stream Resource Flow Requirements: An Assessment. US Fish and Wildlife Service, Office of Biological Services, Western Water Association: Washington DC.
- Stanfield, L.W. and D.A. Jackson. 2011. Understanding the factors that influence headwater stream flows in response to storm events. *Journal of the American Water Resources Association* 47(2):315-336.
- Stauffer, J.C., R.M. Goldstein, and R. M. Newman. 2000 Relationship of wooded riparian zones and runoff potential to fish community composition in agricultural streams. *Canadian Journal of Fisheries and Aquatic Sciences* 57:307–316.
- Stein, B.A., and Flack, S.R. 1997. Species report card: The state of U.S. plants and animals. The Nature Conservancy, in cooperation with the Natural Heritage Network, Arlington, Va.
- Stewardson, M.J. and C.J. Gippel. 2003. Incorporating Flow variability into environmental Flow Regimes using the Flow Events Method. *River Research and Applications* 19:459-472.
- Strahler, A.N. 1957. Quantitative Analysis of watershed geomorphology. *Transactions of the American Geophysical Union* 8(6):913-920
- Strickler, A. 1923. Beitrage zur frage der geschwindigkeits-formel und der rauheitszahlen ffr strome, kanale und geschlossene leitungen. *Mitteilungen des eidgen6ssischer Amtes fur Wasserwirtschaft, Bern, Switzerland*, n. 16.
- Sutherland, A.B., J.L. Meyer, and E.P. Gardiner. 2002. Effects of land cover on sediment regime and fish assemblage structure in four southern Appalachian streams. *Freshwater Biology* 47:1791–1805.
- Swales S. and J.H. Harris. 1995. The expert panel assessment method (EPAM): a new tool for determining environmental flows in regulated rivers. In *The Ecological Basis for River Management*, Harper D.M, Ferguson A.J.D (eds). John Wiley & Sons: New York; 125–134.
- Swank W.T., Swift L.W. & Douglass J.E. 1988. Stream-flow changes associated with forest cutting, species conversions, and natural disturbances. *Ecological Studies* 66:297-312.
- Swank, W.T. and D. A. Crossley Jr. 1988. Streamflow Changes Associated with Forest Cutting, Species Conversions, and Natural Disturbances. *Ecological Studies*, 66(Forest Hydrology and Ecology at Coweeta):290-312.
- Sweet, W.V. and J.W. Geratz. 2003. Bankfull hydraulic geometry relationships and recurrence intervals for North Carolina's coastal plain. *Journal of the American Water Resources Association (JAWRA)* 39(4):861-871.
- Tenant, D.L. 1976. Instream Flow Regimens for Fish, Wildlife, Recreation and Related Environmental Resources. *Fisheries*, 1(4):6-10.
- Tharme, R.E. 2003. A global perspective on the environmental flow assessment: Emerging trends in the development and application of environmental flow methodologies for rivers. *River Res. Applic.* 19:397–441

- Tharme, R.E. 1996. Review of the International Methodologies for the Quantification of the Instream Flow Requirements of Rivers. Water Law Review Final Report for Policy Development for the Department of Water Affairs and Forestry, Pretoria.
- Tharme, R.E. and J.M. King. 1998. Development of the Building Block Methodology for instream flow assessments, and supporting research on the effects of different magnitude flows on riverine ecosystems. Water Research Commission Report No. 576/1/98. pp. 452.
- Thomas, W.A., R.R. Copeland, and D.N. McComas. 2003. SAM hydraulic design package for channels. U.S. Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory. Vicksburg, MS.
- Thomas, M.C., F. Sheldon, J. Roberts, J. Harris, and T.J. Hillman. 1996. Scientific Panel Assessment of Environmental Flows for the Barwon-Darling River. Report for the New South Wales Dep. Of Land and Water Conservation, Parramatta; 161.
- Thorne, C.R., R.G. Allen, and A. Simon. 1996. Geomorphological River Channel Reconnaissance for River Analysis, Engineering and Management. Transactions of the Institute of British Geographers, New Series, 21(3):469-483.
- Trimble, S.W. 2009. Fluvial processes, morphology and sediment budgets in the Coon Creek Basin, WI, USA, 1975-1993. *Geomorphology* 108:8-23.
- Ward, A.D., & Trimble, S.W. (2004). *Environmental hydrology*. CRC Press. (p. 475) Retrieved from <http://books.google.com/books?id=yANwmTjf588C&pgis=1>
- Tufford, D.L., C.L. Samarghitan, H.N. McKellar Jr., D.E. Porter, and J.R. Hussey. 2003. Impacts of urbanization on nutrient concentrations in small southeastern coastal streams. *Journal of the American Water Resources Association (JAWRA)* 39(2):301-312.
- United States Department of Agriculture, Natural Resources Conservation Service (USDA-NRCS). 2004. NRCS National Engineering Handbook. USDA National Resources Conservation Service, Washington, DC. Available at: www.wcc.nrcs.usda.gov/hydro/hydro-techref-neh-630.html.
- United States Senate, 1972-2002. Federal Water Pollution Control Act. Washington, D.C.
- Wang, L., J. Lyons and P. Kanehl. 1998. Development and Evaluation of a Habitat Rating System for Low-Gradient Wisconsin Streams. *North American Journal of Fisheries Management* 18:775-785.
- Wang, L., J. Lyons, P. Kanehl, and R. Gatti. 1997. Influences of Watershed Land Use on Habitat Quality and Biotic Integrity in Wisconsin Streams. *Fisheries* 22(6):6-12.
- Wang, L., J. Lyons, P. Rasmussen, P. Seelbach, T. Simon, M. Wiley, P. Kanehl, E. Baker, S. Niemela, and P.M. Stewart. 2003. Watershed, reach, and riparian influences on stream fish assemblages in the Northern Lakes and Forest Ecoregion, U. S. A. *Canadian Journal of Fisheries and Aquatic Sciences* 60:491-505.
- Wilkerson, G.V. 2008. Improved Bankfull Discharge Prediction Using a 2-Year Recurrence-Period Discharge. *Journal of American Water Resources Association (JAWRA)* 44(1):243-258.
- Williams, P.G. 1978. Bankfull discharge of rivers. *Water Resources Research* 14:1141-1154.
- Williams, P.R. and S.J. McHugh. 1990. Water Marketing and Instream Flows: The Next Step in Protecting California's Instream Values. *Stanford Environmental Law Journal*, Vol. 9:132.
- Wilson, C.A.M.E. and M. S. Horitt. 2002. Measuring the flow resistance of submerged grass. *Hydrological Processes* 16:2589-2598.

- Wittenberg, H. 2003. Effects of season and man-made changes on baseflow and flow recession: case studies. *Hydrological Processes* 17:2113-2123.
- Wolman M.G. and L.B. Leopold. 1957. River flood plains: Some observation on their formation. US Geological Survey Professional Paper, 282:87-109.
- Wolman M.G. 1955. The natural channel of Brandywine Creek, Pennsylvania. US Geological Survey Professional Paper 282:86-109.
- Wolman, M.G. and J.P. Miller. 1960. Frequency of Forces in Geomorphic Processes. *The Journal of Geology* 68(1):54-74.
- Woo, Ming-Ko and J.M. Waddington. 1990. Effects of Beaver Das on Subarctic Wetland Hydrology. *Arctic* 43(3):223-230.
- Wood-Smith, R.D. and J.M. Buffington, 1996. Multivariate geomorphic analysis of forest stream: Implication for assessment of land use impacts on channel condition. *Earth Surface Processes and Landforms* 21:277-393.
- WMO: World Meteorological Organization. 1974. International Glossary of Hydrology. WMO, Geneva.
- Wright, J.P., C.G. Jones, and A.S. Flecker. 2002. An ecosystem engineer, the beaver, increases species richness at the landscape scale. *Oecologia*, 132:96-101.
- Wright, S. and G. Parker. 2004. Flow Resistance and Suspended Load in Sand-Bed Rivers: Simplified Stratification Model. *Journal of Hydraulic Engineering* 130(8):796-805.
- Xu, Y.J., J.A Burger, W.M. Aust, S.C. Patterson, M. Miwa, and D.P. Preston. 2002. Changes in surface water table depth and soil physical properties after harvest and establishment of loblolly pine (*Pinus taeda* L.) in Atlantic coastal plain wetlands of South Carolina. *Soil and Tillage Research* 63:109-121.
- Yoder, C.O. and E.T. Rankin. 1998. The Role of Biological Indicators in a State Water Quality Management Process. *Environmental Monitoring and Assessment* 51(1-2):61-88.
- Young, W.J., J.R. Davis, K.H. Bonner, and P.G. Fairweather. 1995. The Feasibility of a Decision Support System for Environmental Flows. CSIRO Division of Water Resources, Consultancy Report no. 95/19.
- Zalewski, M., R.J. Naiman, and J.S. Alabaster. 1985. The regulation of riverine fish communities by a continuum of abiotic-biotic factors. Symposium on Habitat Modification and Freshwater Fisheries, Aarhus (Denmark).